

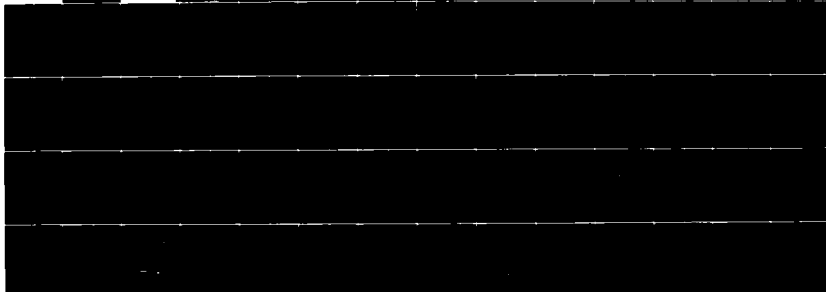
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VISUALIZATION OF THE FLOW AT THE TIP OF A HIGH SPEED
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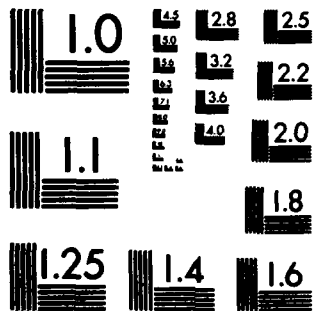
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axial flow turbine rotor blade - an assessment of
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J.P. Bindon, D. Adler

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The basic flow mechanisms are presented for leakage and boundary layer flows at the tips of axial turbine rotors. Various methods for visualization the flows near a rotating turbine tip are assessed. These include smoke injection, spark tracers, pulsed lasers and fluorescent traces. Experimental results are presented for flow visualization by seeding with fluorescent droplets.					
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Summary

↪ The field of flow visualisation has been reviewed and its application to the study of the flow near the tip of an unshrouded axial turbine rotor discussed in detail. The logical conceptualisation of experiments which could lead to a final understanding of the flow structure was developed and how this leads to test turbine design philosophy is suggested.

As outlined in Reference 1, the rotor periodicity shed by the stator requires that particle or pulse tracing is needed rather than the more universal continuous streamline trace which arises from a continuous tracer injection at a point in a flow. While the whole field of flow visualisation at a rotor tip is demanding because of its very nature, pulse tracking will place a greater demand on the development of new skills and techniques. Since streamline tracking is somewhat more standard, these demands will not be as great.

A fundamental choice does however need to be made between the two categories of methods.

In terms of an experimental philosophy it is suggested that a progression of tests each with an increasing degree of difficulty and similarity to the real situation be done. This is to obviate the possible investment of effort without significant results and to follow the kind of progression of knowledge that has taken place in turbomachinery.

↪ The suggested experimental turbine should thus, always with the facility of infinitely variable Mach Number, model the following:

- 1) stationary annular cascade with tip clearance inside a stationary outer endwall;

- 2) Stationary annular cascade with tip clearance inside a moving endwall ;
- 3) The transfer of flow visualisation techniques developed into the rotating frame ;
- 4) Fully rotating rotor with no inlet periodicity ;
- 5) Fully rotating rotor with inlet periodicity. (Israli)

Because the requirements of pulse tracing will only be needed in the last stage, it is suggested that a dual effort be embarked on, a continuous streamline method and a particle tracking method.

The following continuous streamline methods were identified and, in order of intuitive rather than proven selection are:

- 1) Streamwise spark tracer
- 2) Luminescent tracer injection
- 3) Laser smoke generation from blade or probe surface
- 4) Laser smoke from continuously injected oil
- 5) Fluorescent tracer injection
- 6) Thermal tracer tracking using infra red.

Some of the methods are more applicable than others to the various zones of flow and some are not as suitable to a moving rotor as others.

The following pulse tracking methods are, again in an intuitive order of preference:

- 1) Laser or spark pulse with luminescent seeding and photographic recording.
- 2) Laser pulse with luminescent seeding and tracking via coordinates of focussed photomultiplier
- 3) Laser pulse with fixed thermal sensor and tracking via coordinates of input pulse
- 4) Laser or spark pulse with infra red or thermal image tracking
- 5) Localised smoke pockets generated by laser or spark pulse in an oil seeded flow
- 6) Single spot laser sensor with laser pulse evaporated seeding
- 7) Two spot laser
- 8) Fluorescent pulse produced by laser evaporation of solid aerosols.

Since the final choice will depend heavily on the use of ultra sensitive photon recording systems (Numbers 1, 2 and 4) it is suggested that a study be made of the field of image intensifiers, low light devices, TV cameras and thermal imaging devices as well as of luminescent emission from various substances.

Introduction and definition of flow visualisation

Axial turbomachinery flows have been examined experimentally and analytically so that manufacturers have confidence in the designs produced. An area however where more confidence is needed is in the tip region of an unshrouded axial turbine where the cooling of the metal on the pressure side is critical.

In Reference 1, the literature was reviewed and revealed that flows in the important pressure side tip corner have not been as widely studied as the flow in the suction corner where most of the leakage and secondary flow losses are concentrated. It is thus felt that there is a need to understand the flow mechanisms at work and qualitative flow visualisation should precede quantitative anemometry since it is hoped that the streamlines seen will reveal the basic flow types, any unexpected phenomena and also lead to a formulation and theory of the basic flow structure. It is proposed that the flow visualisation be carried out in a machine which is as fully representative as possible of the real situation in terms of Mach Number, turbulence and of the actual configuration of a moving rotor preceded by a stationary nozzle.

The term "flow visualisation" can mean different things in different contexts. In the context implied here it will be taken in the very broadest sense as any means by which flow phenomena can be reduced to a graphic image against a background of the bounding flow geometry. The means should be particularly sensitive to revealing the unusual and unexpected such as vortices, separations and reattachments and should preferably at some stage show streamlines. To reduce the effort, the technique must map a volume more quickly and more comprehensively than would microscopic velocity and angle measurements, which, if fine enough could be used to

construct a graphic image. Thus a probe which could measure flow direction by a visual recording does no more than a 5 hole pitot probe or a hot wire anemometer and thus will not qualify as "flow visualisation". If however, a sensor were found to respond to an upstream injection of a tracer, and no visual output were available and the point of injection can be gradually moved upstream while keeping the sensor in the tracer stream, then the system will qualify as "flow visualisation" since a reasonably long path has been identified and not "constructed". The streamline path is known via the coordinates of the injector and not via a visual means and thus this non visual means satisfies the definition.

To provide a basis for the study in terms of examining what is known and what is to be expected of the tip region behavior, Reference 1 has given a logical description of the flow regimes. It was shown that the flows are expected to have high turbulence and intense shear flow mixing regions both of which will make flow visualisation difficult apart from the problems of viewing in the rotating field. An additional complexity was revealed relating to the nozzle generated flow periodicity in the rotor. In the presence of any tangential nonuniformity, particularly that of angle, the continuous injection of a tracer cannot identify streamlines. The alternatives are therefore to eliminate all periodicity or to develop techniques of short duration or pulse tracer injection in which a small volume of fluid is identified and traced through the rotor.

Reference 1 indicated that 4 regimes of flow can be expected at the tip which have varying importance with respect to blade cooling, varying degrees of understanding arising from previous work and almost certainly varying requirements in terms of flow visualisation. The most important regime is that of the mainstream flow entering the rotor ahead of the pressure corner and on its passage through the rotor, passes over the tip of a blade as leakage flow. The next most important region is that in the cavity between the blade tip and the outer annulus wall.

In this report, the visualisation of turbomachinery flows will be reviewed as well as techniques of more general application. Various methods and adaptations will then be suggested as having possible application to the present situation. Most of the ideas will be somewhat tentative wherein it is acknowledged that implementation will require lengthy and painstaking work of a multidisciplinary nature, the end result possibly not being complete success but only the establishment of the limitations of the method.

The report will also present a conceptual philosophy regarding the experimental turbine which will best serve the various flow and flow visualisation criteria identified. It has already been suggested in Reference 1 that since the present knowledge and understanding of turbomachinery flows has been built up by a vast series of increasingly complex experiments where various phenomena were modelled, the best rig may be one which can take the researcher through a progressive series of tests of increasing complexity. Each stage would deliver results before passing on to a situation which could potentially be beyond the ability of both budget and physics to solve. The

simplest example of this concept relates to the speed of the rig. If the rig were infinitely variable from zero through Mach Number unity, the limits of meaningful flow visualisation may be shown to be Mach 0.1. If however the rig were a constant speed device, no flow visualisation results could ever be obtained and there would be no logical end to the effort. Other aspects of how a rig can serve a progression of studies will be identified.

Review of flow visualisation relevant to turbomachinery

In a large scale low speed radial compressor, Reference 2 described the streamline flow in the impeller using smoke injection and an observer rotating with the rig. In Reference 3 the boundary layer development in a radial compressor was shown using a spark tracer method. Figure 1 shows that when two conductors are imbedded on the walls of the channel to be studied and a high voltage applied accross the conductors, a long spark occurs at the shortest distance or where sharp points lead to concentrations of field intensity. The spark ionises the air in a long envelope of molecules. These excited molecules flow downstream, normally approximately in the direction of the conductors. Since these ionised molecules form a path of lower resistance than ground state air, a subsequent voltage pulse will follow the original envelope and re-energise the molecules. The shape of the second spark thus denotes the progress of the molecule envelope since the first spark. A successive series of sparks thus provides information of a limited nature. Streamlines as such are not revealed but the method can reveal unusual phenomena when they occur.

In References 4 smoke injection showed the horseshoe vortex structure at the leading edge of a turbine blade in a linear cascade while Reference 5 showed the same phenomena in the stator of an axial compressor. The use of coloured smoke, Reference 6, enables the individual traces made in a low speed (2 m/s) turbine cascade to be more easily separated.

Numerous studies of limiting streamline flow have been made. While these deal only with particle flow in contact with the surface, the flow phenomena more deeply embedded in the flow can often be implied. Reference 7 used ink injection onto the papered endwall of a linear turbine cascade while References 8 & 9 used white oil either painted or dotted onto the endwall and blade surfaces of an annular turbine cascade. Flow separations are most easily

be applicable to a turbine rotor since the fluid movement would be affected by centrifugal forces. To obviate this and show the actual limiting streamline flows on the rotating blades of a large low speed turbine, ammonia seeded air was injected at various points on the blade surface on which ammonia sensitive Ozalid paper was attached was used in Reference 10.

References 11 & 12 specifically addressed the problems of tip clearance effects in axial compressors using limiting streamline streak techniques.

The most important study regarding recent work in turbomachinery flow visualisation is that described in References 13 and 14 on a high speed axial compressor. A completely seeded flow was pulsed with a laser sheet and the output intensity recorded via an image intensifier tube. The system of fluorescence was that of biacetyl (2, 3 butanedione $\text{CH}_3\text{COCOCH}_3$, a dairy product flavouring) vapour which will both fluoresce with a $1 \mu\text{s}$ lifetime or phosphoresce (luminesce) with a 1.8 ms lifetime. As shown in Figure 3 a 25 mJ , $0.3 \mu\text{s}$ pulse from a dye laser was directed via an upstream mirror into the meridional plane to obtain an exposure from the blowdown facility which used an Argon, Freon 12 working fluid which eliminated oxygen which is a strong quencher of the emitted fluorescence. These works should provide valuable information in assessing fluorescent, luminescent and pulsed possibilities in the report. It should be noted however that the result was not "flow visualisation" in the sense of showing streamline flow. It was more an optical anemometry technique from which some normal flow data can be derived from the light intensity measurements.

Flow visualisation techniques which have been used in other than turbomachinery applications and which may have application in the present problem are aerosol illumination and laser fluorescence. Reference 15

describes the injection of liquid ether into the boundary layer of a flat plate. A sheet of laser light was directed into the wake of the plate as shown in Figure 2 and the light scattered by the ether aerosol particles was recorded photographically. Apart from the difficulty of accessing turbine rotor flows with a light sheet and orientating a camera appropriately, the problems of light reflections from windows and blades may swamp the signal. Thus the use of laser induced fluorescence, which can be tuned to fluoresce at a different wavelength from the exciting light may mean that only the light of interest can be allowed to enter the recording device. Reference 16 illustrates the technique by photographing a Mach 2.5 nitrogen jet seeded with iodine vapour as the fluorescing tracer molecule. A laser light sheet was used and results taken using light at normally fluorescing wavelengths and, by detuning the laser light with an etalon to give off resonant fluorescence which is at a different wavelength. Such scattered light is independent of pressure and thus be used for tracer concentration measurement.

In Reference 17 both laser illumination and laser fluorescence were used to map seeding concentrations in a turbulent jet. Using a pulsed 2W argon ion laser, a cylindrical lens and a TV camera as a recording device, the light intensity at 10000 positions could be obtained from the recording of a single laser pulse in the illumination mode. In the fluorescent mode, also using iodine vapour as the seeding molecule, the TV camera integrated the output from many pulses since the light intensity was 10^3 times weaker.

It should finally be noted that countless studies have been performed on visualising low speed laminar and turbulent phenomena as References 18 and 20 describe. Few of these techniques are possible in the present situation.

It is well known that the doppler shift from molecules rather than from aerosols can be used to measure the gas velocity provided the Mach numbers are high. In Reference 21, the doppler signal used for velocity measurements was enhanced by seeding the flow with iodine vapour and the velocity in a Mach 5 nitrogen jet measured via a photo diode image intensifier. The fluorescing intensity field was also photographed and provided an image which reflected the iodine image.

Since the concept of two intersecting pulsed laser beams to energise a small volume of phosphorescently seeded flow, the single pencil beam tracer work of Reference 22 is of interest even although the experiments were in liquid. The laser beam energised a streak at right angles to the flow and the delayed luminescent emissions recorded 16, 16.25, 16.5, 16.75 etc. ms. after the excitation on a night vision type image intensifier. The results showed the development of a boundary layer in a tube.

Brief Inventory of Flow Visualisation Technique.

Before a more in depth analysis of complete systems is made in the next section, an inventory of flow visualisation techniques or components of techniques is made here. The reason is to provide a list of ideas which may or may not have relevance to flow visualisation and the problem at hand. At times only a component is given which may form a complete system in association with other components.

1. Fluorescence Molecules are excited by incident photons and, as they decay back to the ground state, photons are emitted. The decay is relatively rapid and it is unlikely that any trace will be seen after the exciting beam terminates. The emitted light can be at a different wavelength, a factor which could be important when recording near surfaces where reflections from the exciting beam need to be eliminated. Some substances fluoresce with radiation at a particular wavelength e.g. U.V.
2. Luminescence, Phosphorescence, (delayed). Some molecules when excited retain this state for some time before decaying back to the ground state and emitting light. Such a phenomenon may be particularly useful in photo tracking a parcel of pulse illuminated molecules or in seeing a line of seeded material after flooding the whole area. This could be superior to ordinary illumination of aerosols because the background illumination is eliminated from the exposure.

3. Pulsed laser A pulsed laser has the ability to inject large quantities of photons and other radiation into a small volume either as a waisted pencil beam or as a light sheet. If two beams are allowed to intersect, double the light intensity will occur at the crossing and it may be possible to use these doubly excited molecules as point tracers. It will form a non invasive tracer injector with a high degree of freedom in terms of accessing the stationary and the rotating frames.
4. Spark Tracer A high voltage spark is inserted into the flow and, after the emission of photons, the still highly excited envelope of molecules provides the low resistance path for a second voltage pulse a short interval after the first. The shape of the two successive spark traces is an indication of fluid movement in the interval between the pulses. Conductors are normally placed roughly in the direction of flow so that successive sparks may cover the whole flow field. In terms of streamline visualisation it may be possible to place point conductors upstream and downstream between which, after a number of high frequency sparks, will follow a streamline. Closely spaced electrodes will have the ability to send small hot packages downstream which could possibly be tracked.
5. Image Intensifier Tubes Many extremely sensitive devices are commercially available in the form of low light TV cameras, night vision enhancers and thermal target detectors at moderate budget prices.

They have already found application in flow visualisation (References 13, 17 & 20) and the light amplifications are more than equivalent to ultra high speed film and the images in some designs are digital. When coupled with slow decay phosphors, they are able to integrate over a relatively long period of time. Alternatively, a film camera could be used for an exposure of virtually any length of time and thus the tracer origin could be moved to record multiple streamlines on one photograph.

6. Aerosol or smoke injection This is the oldest form of flow visualisation and involves the continuous injection of submicron liquid or solid particles and viewing the track via the scattered light from a flash lamp, photoflood lamp or even sunlight.
7. Continuous tracer injection To continuously feed tracer material to a given point in the flow to create a streamline of seeded material, some form of injection hypodermic is needed. This has often been in the form of a rake for multiple streamline insertion. The injection tube for the present study would have to be in the rotating frame and for convenience, virtually infinitely adjustable with respect to position without stopping the rotor. The aerodynamic forces would make it difficult to design a probe with a minimum of flow interference.
8. Pulse tracer injection This involves the creation of a small volume of fluid which can be traced or tracked as it passes through the region of interest. In periodic flow, this is the only way to correctly determine the path of a streamline.

9. Detector sensor. It is possible not only to record a streamline location via its light emission but also physically via its effect on a sensor. The sensor could be chemical for a flow seeded with a marker species or any other effect to which a sensor could respond. The path of the streamline is thus determined by the physical position of the sensor.
10. Focused photomultiplier This is a sensitive recorder of photons and should be effective in determining the low light levels expected from fluorescence and luminescence. Although this device is a single element of what often occurs in multiples in image intensifiers, it has the ability to be focused by a lens on a particular part of a flow and thus could form a non invasive detector.

Conceptual philosophy for the experimental turbine

Before an in depth assessment and selection is made of flow visualisation techniques, it would seem appropriate to first assemble the desirable and necessary aspects of a test turbine since in the first instance anyway, the product should dictate to the tool and not vice versa. At a later stage the demands of the flow visualisation technique may indicate that an aspect of the turbine must be relaxed.

Flow visualisation at the rotor tip of an axial flow turbine has the following special problems:

- 1) rotating frame measurements necessitating "freezing" of images and complex mechanical access of signals, traverse mechanisms and gas feeding.
- 2) high turbulence which will quickly disperse tracer injections.
- 3) intense shear flows which also contribute to rapid dispersion.
- 4) high gas Mach Numbers and blade speeds.
- 5) tangentially unsteady effects due to upstream and downstream nozzle blades render simple continuous tracer injection impossible.
- 6) the existence of strongly different zones of flow which may require completely different techniques for visualisation,

In terms of what was said in the introduction, it would seem desirable that a test turbine should ideally either be able to gradually introduce each of the above complexity factors or it should be able to turn them on or off at will. Item 1 has already been dealt with and it is obvious that the gas and blade velocity should be infinitely variable from zero up to the selected maximum. Since items 2 and 3 are closely related to Mach Number, it follows that these would also vary from low to high values.

Reference 1 indicated the relative dearth of previous measurements and flow visualisation relating to the tip zone. If the tip leakage flow problem had followed the type of progression of experimental sophistication seen in other aspects of turbomachinery flow, the literature could well have revealed the following, with accompanying predictive modeling at each stage:

- 1) measurement and flow visualisation at the tip of a simple low-speed 3 blade linear cascade with the center blade provided with varying degrees of clearance

- 2) same as 1 except that the fixed tip endwall is replaced with a moving belt to simulate the relative motion of the blade.

- 3) measurement and flow visualisation in the tip clearance region of a low speed annular cascade to model the rotor flow behavior.

- 4) same as in 3 except that the outer casing is rotated to further improve on the rotor model

5) full scale hot and cold turbine tests to assess the applicability of the predictive model at high speed and when the full rotational effects are applied to the rotor flow.

A weakness in the results of 5 would require a vastly different approach than the current situation in which very little of the knowledge is available.

It could thus be argued that the starting point now should be a variable Mach Number 3 blade linear cascade with center blade tip clearance. It is however strongly felt that an annular cascade is not significantly more expensive to build than a linear cascade and the tangential flow uniformity problem is eliminated and radial effects included in the model. The linear cascade model can therefore be left out.

Since in a reaction turbine the rotor has somewhat similar blading to a nozzle, a great deal of phenomenological modeling can be achieved by building a single bladed wheel with tip clearance inside an annulus. If the wheel is locked so that it cannot rotate and the flow enters axially, then the rotor tip flow is modeled without the complexity of items 1 and 5 but also without including the effects of relative motion and true rotor centrifugal effects. The velocity triangles are also not correctly modeled as shown in Figure 4. The correct rotor triangles are shown and the radial equilibrium creates a high reaction tip and a low reaction hub. If the wheel were locked, the "simulated rotor" would have velocity diagrams as given for the nozzle in Figure 4 and the "rotor" blading of the modeled situation should be made accordingly.

With the fixed rotor, a wide range of experiments and techniques can be made and developed, from low to high Mach Numbers, without having to deal with problems 1 and 5. At the end of this stage a deep appreciation of the flow phenomena would have been obtained and the limits of flow visualisation procedures established and even gradually transferred into the rotating plane by allowing the rotor to rotate and ensuring that all the necessary mechanical and optical systems are ready for the rotating frame of reference.

At this stage the option exists of allowing the casing to rotate while still keeping the wheel locked and thus introduce the effect of relative motion as well without yet expanding into the complexity of rotor movement and of the nozzle wake unsteadiness. This would of course be of particular importance if it had been found that only a continuous tracer injection had been successful. The casing could very simply be rotated by attaching vanes to it as shown in Figure 5.

If a pulsed tracer flow visualisation system had been successfully developed at this stage, and it was decided to build a fully fledged turbine to model all aspects of the flow, then the blades currently serving as the rotor model could become the true nozzle and a correct set of rotor blades made. If a uniform flow upstream is desired while implementing the fully fledged rotor model, the nozzle would need to be sufficiently far upstream to allow the wakes and secondary flows to die out. Since this may turn out to be a considerable distance, thought should be given either to manufacturing a special set of thin closely spaced high aspect ratio blades which would have small wakes, or to

using mesh. This aspect would have to be carefully studied since it would be necessary to have the correct inlet angle at the rotor and a mesh would tend to reduce the swirl angle.

In summary therefore, it is possible with a single experimental variable speed (in terms of rotor speed and Mach Number) turbine to stage by stage perform the following experiments:

- 1) Stationary annular cascade with tip clearance inside a stationary outer endwall
- 2) Stationary annular cascade with tip clearance inside a moving endwall
- 3) The development of flow visualisation techniques for the rotating frame of reference using a slowly moving rotor
- 4) Fully rotating rotor with no inlet periodicity
- 5) Fully rotating rotor with inlet periodicity.

It should finally be said that an alternative strategy is possible which would be applicable if it was decided not to implement stage 3 above which converts the instrumentation to operate in the rotating frame. Stage 4 could of course not be implemented but part of stage 5 could, that of the effects of inlet periodicity. If a fully rotating turbine stage consisting of a normal rotor and stator were placed upstream of the test "rotor", these would shed the an almost equivalent "nozzle wake" in the test section especially if the stator were placed some distance upstream to reduce its wake effects. This is illustrated in Figure 6.

Preliminary aspects governing the selection of flow visualisation technique for tip clearance study.

The types of flow to be expected in the tip region and the available developments in flow visualisation have been reviewed in Reference 1 and in this report. The zone flow of prime importance and which should largely determine the selection of flow visualisation equipment, is that near the pressure side corner entering the clearance gap (Zone 1). The next most important area is the flow in the tip gap (Zone 2) and since the flow is so different, the flow visualisation equipment might also be quite different.

The most important aspect with respect to the choice of flow visualisation equipment lies in the means of tracer injection and this in turn is governed by whether the rotor blades will rotate or whether the stationary frame experiments alone will be performed or at least as a separate and preparatory stage to the eventual rotating blade flow examination. There appears to be two kinds of tracer injection:

- 1) a probe of some sort located within the flow
- 2) a non invasive means such as a laser beam or laser spot

The first type has been widely used in many applications but could provide severe mechanical complications when extended into the rotating frame. Some simpler possibilities of taut wire or hypodermic tube will be presented. The second type, while it has been fairly widely used for light sheet fluorescent illumination, has not

been widely used for streamline or flow particle identification. This will therefore mean that new techniques are needed but have the advantage of virtually complete freedom of location without significant mechanical complications in both the fixed and rotating frames. In addition, this means is the only one which will be able to visualise streamlines in periodic flow.

Apart from streamline tracer injection, there appears also to be two distinct categories of tracer detection. The first is again via a probe to which a sensor is attached. As with the case of an injector sting, considerable mechanical complication is involved but they are not as severe since in the most important zones of flow, the streamlines of interest all end close to the blade. Therefore the probe will never be far from the blade and provided it does not serve a "search and find" function, mechanical complications can be reduced to a number of different probes being fixed at different locations. Each probe would identify a separate stream and would require the rig to be stopped and opened if it were a rotating one.

The second type is again non invasive and will most likely be of the form of light and the recording means ultimately photographic. The advantages of this means are the same as for the non invasive tracer injector.

In the light of these preliminary considerations, it is suggested that a system of non invasive injection and detection be pursued as it is believed feasible from the assessment made of the literature. In the next section therefore the method of laser pulse injection will be discussed in greater detail as will the question of trace detection.

Despite the above suggestion, it may be decided at some stage in the future investigation, to use a different system of the invasive type. This type of system will also therefore be discussed in more detail. Finally, a host of ideas are briefly described which may bear fruit even if only as seed material for later conceptual development.

Application of laser pulsed tracer injection

In order to visualise flows in the presence of periodicity, it is essential to use a pulse type tracer marker which moves as a particle through the flow field. (Reference 1). Continuous marking of a streamline produces a blurred result or an inaccurate result. Since a laser has the ability for short duration pulses, it would seem the obvious tool although an electric discharge will do the same thing (see next section).

The pulse can take on any form, parallel beam, plane sheet, waisted beam, intersecting parallel beams and intersecting waisted beams, depending on the optical system used. Laser light has widely been used to induce fluorescence. However, in the present application this will not work because a pulsed effect is not possible. If a pulsed system is to work then a completely seeded flow must be made to luminesce or phosphoresce from a small volume of fluid, that is emit delayed photons after the pulse has been applied. References 13 and 22 have identified substances which will luminesce for a period of time after the energising pulse. Provided the photons from the energising pulse does not swamp the exposure from the luminescing particles, the passage of the particles can be recorded photographically, if need be after image amplification.

The most obvious form of pulse is that from the intersection of 2 or more waisted beams giving a small volume with 2 or 3 times more light intensity than that of the beams immediately adjacent to the spot. If the light intensity in the spot is such as to just saturate the substance, then the particle should glow more intensely than the fluid alongside the

particle which has been only partially excited. The system is illustrated in Figure 7 and, because of the optics for the two converging beams, looks somewhat similar to an LDV setup. Depending on where the viewing optics and recording system is placed, more or less of the side "tails" will be seen.

While the ideal system is obviously the focused spot, a great deal of information may be provided by a simple laser pencil beam energising a strip of fluid within a flow. Bearing in mind that an aspect of flow visualisation is to cover as wide a field as possible in order to provide a global overview of the flow, the motion of the strip of fluid may be particularly revealing of some phenomena such as a vortex. The strip illumination process could well be used to advantage at the beginning of the study. When applied to the flow in the clearance gap, a strip of energised particles would reveal the velocity profile as shown in Figure 8. In such a system, the aperture must be opened at specific intervals to show the individual lines drawn. A time or integrated exposure would probably be easier and would provide the same information.

The fluorescing phenomena is subject to molecular quenching whereby the emitted light is not a function of the concentration of the seeding substance. When concentration has therefore been measured using an optical system, the molecular species carrying the seed molecules must be chosen so as not to quench the process. The effect of the working fluid on the luminescing emissions is not known. However it is obvious that the working fluid, whatever it is, may have to be

completely seeded in a closed circuit or it may be possible to seed certain segments of the flow with the seeding material going to loss as is often done with LDV seeding.

The recording systems of References 13 & 22 contained in both instances image intensifiers as did many other reported optical systems. It is beyond the scope of this report to review this field but it is strongly suggested that a review is conducted and a suitable device selected. This will enable extremely low light levels to be recorded and may also provide facilities for both eye viewing and photography of the integrated result of many pulses. In view of the expected low light levels, the test turbine should be located in a special windowless laboratory so that all daylight may be excluded without interfering with other laboratory activities.

The pulsed laser system may function with a fixed downstream detector sensor as outlined below and do away with the need of a luminescent seeding material and optical recording system. Although the freedom of movement is lost, the non invasive element is partly retained since only the downstream end of the streamline has a physical intrusion into the flow. Such freedom of movement is however retained for the upstream end of a streamline and this freedom can be used to "find", by manual adjustment, a condition which meets whatever criteria have been set up to detect the energised particle "reaching" the downstream sensor target.

An essential ingredient in such a manual manipulation scheme is that the target signal must be rapid (e.g. oscilloscope trace) so that the operator can respond without a long wait. (e.g. the development of a photographic film)

Referring to Figure 9, a pinpoint sensor (e.g. a small thermocouple or thermistor) is attached to the blade at the end point of a desired streamline. This is particularly of use in tracking Zone 1 (see Reference 1) streamlines since the desired endpoints are precisely known and close to the blade which minimises the length of the sensor stem which could even be on the top of the blade on the flat tip surface. The opposite is true for Zone 3 where the endpoints are not known and could be some distance from the blade, even downstream.

An electronic trigger is attached to some blade "ahead" of the sensor and fires the laser pulse via an adjustable delay timer. When the rotor is stationary, the laser power is turned down and the laser axial position (x) and radial position (y) adjusted such that the target responds. Thus when the rotor is set in motion all that is required is a sweep of the pulse delay for the laser to latch onto the target. Thus the pulse has been easily and simply focused onto the target with a fixed position in both the rotating and stationary frames.

The laser is now moved a short distance upstream. If the step is very small, the target should still respond although not perhaps

at peak value since only the edges of the pulse could be encountering the target. By trial and error the vertical distance y and tangential distance can be adjusted until target output is a maximum (Note that z may be adjusted via the laser position or via the timer provided it is calibrated). Thus without ever "loosing" the target in terms of y and z adjustment, the laser can gradually be moved upstream. Even if the target is "lost" it should be not be a difficult task to sweep with y and z until it is found. At any point the x, y, z values can be recorded thus providing a segment in the construction of the streamline.

As the distance upstream increases, mixing will disperse the trace. Turbulence will also begin to make each successive signal different. An algorithm may have to be devised which not only finds the core from a series of traces executed at known intervals of x and y but which also builds up a theoretical trace shape from a number of traces which vary randomly due to turbulence. This is illustrated in Figure 10. Such an algorithm will have to be rapidly executed in order to allow the operator to progress. A computer based data acquisition and processing system will thus be essential to extend the length of the constructed streamline.

Eventually turbulence and mixing will so dilute the signal that further upstream movements are no longer possible. At this stage the target can be moved to the last reliably recorded location and the process repeated.

The most convenient way of mounting a sensor may be to attach it to a taught wire as illustrated in Figure 13, the two legs of the wire serving as conductors.

In the foregoing, a fixed downstream detector was used. It should be possible to use a non invasive system such as a focused photo multiplier. In this case either the pulse injector or the pulse detector could be the device that is moved to perform the "search and find" task. Since the trailing sensor is now also non invasive, its location with respect to the rotor blade is now also determined by a delay timer triggered by the same switch as the pulse timer. Because there is complete freedom of movement on both ends of the streamtube segment, it should also be possible to march right along the whole length of a streamline without having to stop the rig for any sensor relocation.

Application of a spark tracer method to streamwise flow visualisation

In terms of the methods previously discussed which require a tracer probe to be located at the origin of a streamline, the spark tracer method appears to offer better possibilities in overcoming the problems of mixing, turbulence and the visual recording of traces. The sting may be slightly less complicated since it will not need to carry tracer gases.

As described already, the spark tracer has previously been used to ionise a path essentially at right angles to the flow. Successive spark paths thus indicate the progress of fluid in the time elapsed. Streamwise or streamline flow may be visualised by placing electrodes essentially but not exactly upstream and downstream in the flow as shown in Figure 11. When a high voltage is applied, a straight line spark will jump between the two electrodes. After a short period of time, all the ionised particles will have moved downstream a small distance as shown. If a second voltage pulse is applied, it will follow the path of least resistance and thus the small gap between the upstream electrode and the ionised path is energised as well as the original fluid. This energisation of the small gap is most important because here the shape of the spark is essentially a tangent to the streamline. After many sparks, the whole of the spark trace consists of flow tangents and if the frequency is high enough and the flow curvature not severe, the tangents will represent the flow path.

A major problem with such a method is the large voltage needed for the large axial gap. Figure 12 therefore shows that if a high frequency spark were created in the vicinity of the upstream electrode which consists of two closely spaced conductors, a streamtube of energetic molecules will trace a streamline between the two electrodes. If a pulse is now applied, this ionised path will become visible. If mixing has

destroyed the structure of the energised fluid furthest from the upstream electrode, or if the excited state lifetime is not long enough (Reference 19 suggests it is only 10^{-4} sec), then successive sparks are needed before the correct streamline shape is achieved and the objective of reducing the voltage would not have been fully realised.

The spark streamwise tracer method cannot however be used for periodically varying flow because it involves essentially a continuous tracer injection. Although the luminescing species will most likely be destroyed within the high temperature spark core, a spark will emit photons and the zone surrounding the spark will luminesce as a small pulse. The pulsed laser techniques previously discussed will then be applicable. In the next section the possibility will be discussed of sensing the thermal radiation from the high temperature spark core.

When applied to streamlines in Zone 1, the streamline origins are expected to be fairly localised and the streamline terminations are always along the blade tip. The downstream electrode thus becomes the blade tip and is shown in Figure 13. The upstream electrode and ionised path generator could be in the form of two taut wires terminating in a glass bead. The taut wire is relatively easily traversed laterally using a motorised spool system.

Vertical movement could be achieved by stopping the rig and threading the wire through the test blade via a different hole or notch.

Some alternative methods of triggering the spark in the streamline direction are shown in Figure 14. These eliminate the need for a second power supply providing the high frequency ionising pulses. Such methods will not provide a streamline shaped spark the first time a spark occurs but relies on successive sparks ultimately reaching the correct shape. The first method involves a very fine fusible wire between the upstream taut wire electrode and the upper blade surface plate. When the first voltage pulse occurs, the wire fuses, vaporises and heats the air to provide a path for successive sparks. The second method involves insulating the leading edge only of a complete blade forming the downstream electrode. The taut wire electrode which now includes a specially shaped "trigger finger" must be traversed towards the conducting blade surface until the first spark occurs. The wire is then withdrawn to the location desired and the ionised stream follows the ionised path to any naturally occurring termination anywhere on the blade surface.

Other possibilities for flow visualisation

In this section some other possibilities for flow visualisation will be briefly explored.

- 1) Thermal pulse tracing Some night vision devices respond to infra red or thermal radiations rather than to photons. This may present the possibility of tracking by its thermal emissions a volume of gas heated by a pulsed or continuous laser or by a single spark or a succession of sparks. The working fluid could be seeded with species having a stronger emission spectrum than air and background radiation could be reduced so as not to swamp the small signal from the gas phase which may have to be integrated over many cycles before an output is obtained.
- 2) Pulsed Fluorescence Fluorescence has not been discussed since it would involve the continuous seeding of a streamline. If however an aerosol substance could be found which had a relatively low fluorescent emission as a solid but which when vaporised via a laser pulse, evaporated and produced a stronger emission, then the well known laser induced fluorescent techniques may become applicable. Sources other than that of a laser could be used, e.g. UV. An example of such an aerosol would be an alcohol and iodine spray. After the alcohol evaporates, particles of iodine would form the aerosol. At the high

temperatures available within a laser or spark pulse, high localised iodine concentrations should be possible before cooling and recondensation takes place.

3) Single spot laser sensor The LDV system cannot be used near walls or blades since reflections from windows and surfaces swamp the signal with noise. If the photomultiplier output were used only as a detector of aerosols, then the high frequency doppler signal and the noise could be filtered out, the result being an ability to detect particles far closer to walls and windows than is normally the case. In a flow continuously seeded with an aerosol, the photomultiplier output would show a random passage of particles.

If a laser or spark were used to evaporate all the particles within a volume significantly larger than the mean distance between particles, then the "no particle" condition would be a flat output on the signal as shown. The laser detector beams can be used to progressively locate or "find" the downstream slug position in much the same way as previously described for using a fixed downstream sensor and an adjustable upstream injector. The advantage is complete freedom of movement of both injector and sensor. The removal of particles via evaporation is unlikely to be affected by cooling since recondensation will be on a molecular level. The zone will however be reseeded by mixing.

4) Two spot laser The L2V system involves the detection of time of flight of an aerosol between two laser beams or spots. If the position of one spot could be manually adjusted in 3 dimensions with respect to the other, then the one becomes the "pulse" injector and the other the detector. By progressively moving the one spot away from the other and keeping the particles correlated, the streamline path can be constructed. It is not known to what extent such a laser system would improve on the rear wall problem.

5) Localised smoke pockets It is well known that smoke is created via the evaporation and subsequent condensation of oil into a dense mist of small aerosols. Such a process could possibly be created in situ within a stream of fluid via the heating of large oil aerosols using a pulsed laser beam or a spark. When recondensation occurs, the medium will be opaque. Such a process could either be a pulses which would satisfy the conditions of periodic flow visualisation, or it could be continuous. The latter would be equivalent to the injection of smoke via an injection tube. Such a pulsed smoke generator has been used before but from a fixed surface painted with the substance (Reference 23).

6) Laser pulse smoke generation from surface The generation of smoke from a solid surface may be possible in the present situation via a taut wire coated with the substance and stretched across the inlet to the blades at the appropriate position as shown in Figure 15. Such a taut wire concept will provide the minimum flow interference and provides perhaps the easiest means to overcome the severe aerodynamic forces. The wire can also be threaded through the blade. Due to the time constant of the wire and coated surface, it is unlikely that a smoke pulse will be of short enough duration to form a tracer pulse and the result will be more like a continuously injected trace and thus cannot be used when the upstream flow is periodic. However, a single coating and a single exposure could provide the equivalent of a smoke rake and stepping the laser along the wire could provide a number of traces. The principle can also easily be applied to the blade tip surface and to the outer wall shear flow layer as shown in Figure 16. The paint will of course have to be transparent for viewing from the outside.

7) Laser evaporation of continuously injected oil. Since hypodermic tubing is available in extremely small sizes, it may be possible to extend the taut wire concept to actually exuding oil continuously at a point and then either evaporating it continuously using a laser (stationary frame) or as pulses. The exudation of oil is shown in Figure 17. Also shown is the possibility of spraying the oil instead of exuding it. If oil is fed along one leg up to the exit hole and compressed air along the other leg, a spray of mist should result. This mist could then be pulse evaporated as described above under paragraph (5) or it could be continuously evaporated for use in the stationary frame. A convenient way of feeding the oil and air will have to be found as well as of moving the tube laterally to move the injection point and of tensioning the wire. A general layout is suggested in Figure 17 but no details given.

8) Continuously injected fluorescent trace. A fluorescing substance may be injected as a tracer and the area excited by a laser beam. Fluorescence normally requires a high laser power and thus a sensitive image intensifier would be needed even after the area of the beam were reduced to a minimum. The injection techniques presented in Figure 17 would be applicable. Alternative methods of illumination such UV may be more effective than the laser.

9) Continuously injected luminescent trace A luminescing substance may be injected as a tracer using the injection techniques of Figure 17. Since luminescence is created by photons, flash energisation would probably provide the most photons over the trace area and the luminescing trace recorded via a system with a timed shutter to eliminate the energising photons.

Conclusions to the flow visualisation discussion

In the preliminary discussion it was pointed out that major choices would lie between mechanical aspects such as whether the rotor would rotate or not and whether a non invasive system would be used which is mechanically simpler than the arrangement of possibly moving systems of trace injection or trace sensing.

The discussion of flow visualisation with respect to turbines has indicated in addition that a major choice to be made is between a system which will respond to the periodic flow created by the nozzle or a system which is suitable only to rotor flows without upstream variations of flow. The former is of course applicable to all types of flow but will require the development of relatively new pulsed laser techniques in combination with the emissions from special tracer chemicals and the use of ultra sensitive recording techniques involving image intensifier tubes. The latter method could be somewhat more conventional and not as reliant on the physics of new techniques.

In terms of the arguments presented already regarding the type of test turbine, two points should be made. The first is that the inclusion of periodic effects should be the last task to be tackled in the series of flow models identified. The second is that the problems of pulse trace visualisation may prove so severe that no results are forthcoming even on the simplest of cases. It would thus seem imprudent to invest exclusively in one advanced technique which would only have application late in the

project and which would jeopardise the early results. It is therefore suggested that an advanced pulse type system be developed in parallel with a more conventional continuous injection trace type system.

In all eight systems were shown to have the facility to pulse trace. They are:

- 1) Laser or spark pulse with luminescent seeding and photographic trace recording
- 2) Pulsed laser with fixed thermally sensitive target and trace "recording" via coordinates of input pulse
- 3) Pulsed laser with focused photomultiplier tracking sensor and trace "recording" via coordinates of sensor and input pulse
- 4) Laser or spark pulse with infra red or thermal tracking
- 5) Fluorescent pulse produced by laser evaporation of solid aerosols
- 6) Single spot laser sensor with laser pulse evaporated seeding
- 7) Two spot laser sensor
- 8) Localised smoke pockets generated by laser or spark pulse.

Methods 1, 3, 4 & 5 are all heavily dependent on the emission of photons from small volumes of species and the recording of these emissions via ultra sensitive devices. An in depth study of these phenomena is called for before a selection is made.

Systems which are suitable for axisymmetric flow (non periodic)
are:

- 1) Streamwise spark tracer
- 2) Laser smoke generation from blade or taut wire surfaces
- 3) Laser smoke from continuously injected oil
- 4) Continuously injected luminescent trace
- 5) Continuously injected fluorescent trace
- 6) Continuous thermal trace using infra red sensor

The spark tracer method, because of its continuous reenergisation all along the streamline and its intense emission is likely to be less affected than any of the other systems by turbulence and mixing. Laser smoke generation on the blade tip and endwall surface are likely to be useful in those areas. (Zones 2 & 4).

Final assessment of the experimental turbine configuration

Reference 1 and the preliminary assessment of the turbine type in this report provided some basic guidelines for the application of flow visualisation techniques. Now that these have been formulated, the final areas of choice, as far as they have been clarified, can be identified.

The Rotor Hub

The mechanical complexity of probe movement seems to have been reduced to providing a wire tensioning, traversing and tracer feeding scheme of considerably less complexity than for example the rotating traverse gear experimental rigs described in Reference 24. It should however be realised that even if a completely non invasive system is selected exclusively, there is no absolute guarantee of success and therefore allowance should be made in the rotor hub for the later inclusion of such mechanisms. In Figure 18 a simple rotor layout is suggested where the hub allows access at the open end for electrical signal transfer, gas transfer or even mechanical movement transfer. A bearing is provided at the center to align the transfer device. The hub is a simple steel barrel and separate from the disc, thus making this item as replaceable as possible when perhaps new holes need to be drilled for blading etc. The axial length is such as to provide space fore and aft of the blades for the location of any rotating probes. No detail of blade mounting is shown as this depends on the speed of the rotor. In the early stages of the study when speeds are either zero or very low, a simple threaded boss on each blade will suffice. If at a later stage a full speed design is required, a new hub can be made perhaps with a slotted root fixing.

The outer annulus

It has been mentioned that certain flow visualisation techniques call for a special atmosphere within the rig. If such a method were selected it would change completely the suggested progression of tests presented previously since the outer annulus would have to be sealed to prevent leakage of the special atmosphere.

For simple air atmospheres it is suggested that a major investment be made in a ground and polished glass ring to act as the outer annulus and as the window. Such a design could provide the needed freedom of access for any photographic studies and for qualitative non invasive beam probes. It is non conductive and will not interfere with any high voltage spark tracers. If the flow model is examined wherein the outer annulus rotates over stationary rotor blades, the accuracy of the rig is such as to allow it to rotate as suggested in Figure 5, the optical ring being clamped axially as shown in Figure 19 between machined steel rings.

Since experimental rigs call for frequent dismantling for part replacement, probe adjustment or complete rebuilds, care should be given to the outer annulus assembly in terms of how easily it comes apart. In Reference 25 a vertical shaft layout was specifically chosen so that the outer annulus may consist of a series of identical machined rings which slotted together and held in place by gravity only. This concept is illustrated in Figure 19. The rings were of cast aluminium since they do not

need to rotate and are replaceable once a new design needs to be investigated and new holes or access ports need to be machined.

Further details of the experimental turbine are beyond the scope of this report. Obviously once a final selection of the flow visualisation technique has been made and an exact formulation of the progression of experiments made, a detailed design can be done in terms of the mechanical layout, the aerodynamics of the blades and the overall flow and power circuit.

Since an experimental turbine of some versatility and sophistication will be produced, it would be helpful to review what aerodynamic function the rig could serve apart from flow visualisation provided the basic aim of the rig is not jeopardised. The most obvious is to quantify via measurements some of the effects or theories derived from the flow visualisation studies. Because the basic aim is blade cooling this aspect should be the first to be considered. In this respect the ability of the rig to be provided with cooling flows and electronic signals via the central boss transfer mechanism is important.

Other measurements are aerodynamic and here the glass window allows laser access and, if the concept of replaceable rings is followed, these can easily be machined to allow access of standard pitot type probes.

In conclusion, a timely advice is quoted from Reference 26. "Make the easy measurements first and the difficult ones last. Learn as much as possible about the flow before the start of the expensive testing. Beware of shortcuts and compromise. They have a way of coming back to haunt you".

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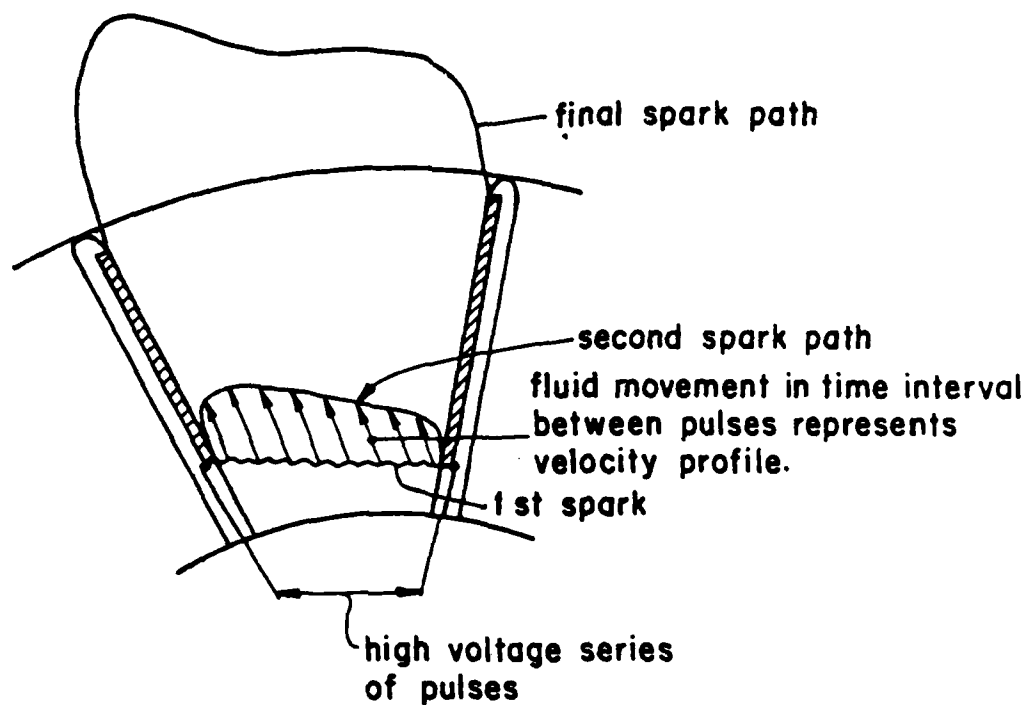


Fig. 1 Crossflow spark tracer method applied to the flow in a radial compressor rotor.

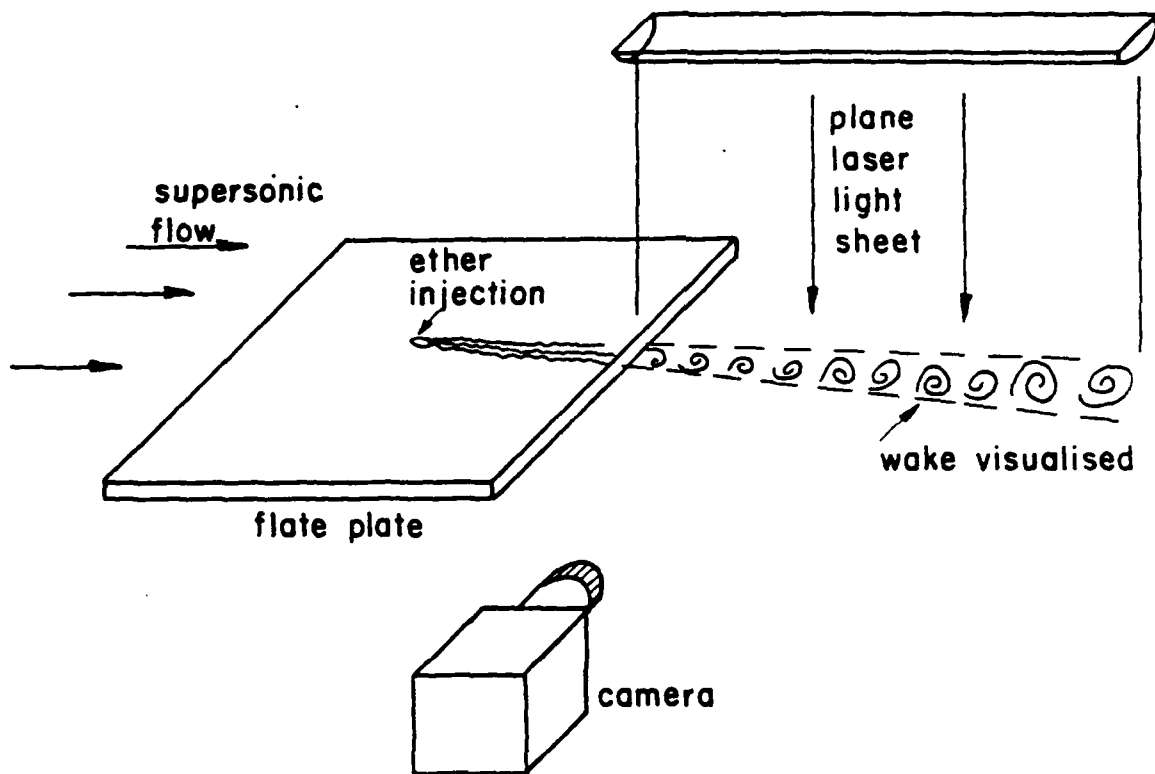


Fig. 2 Aerosol illumination with laser sheet of the supersonic wake flow from a flat plate.

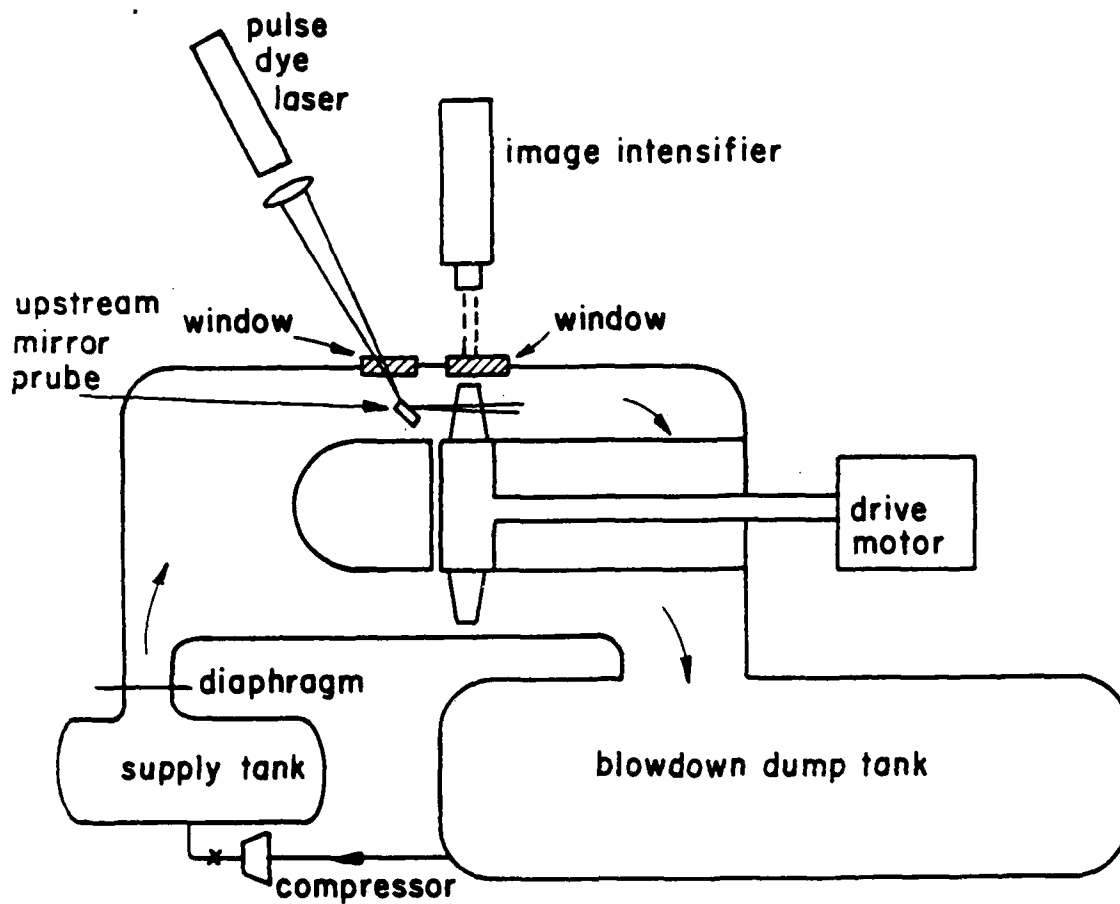


Fig. 3 Schematic of pulsed laser flow visualisation system used on a blowdown argon - freon transonic axial flow compressor.

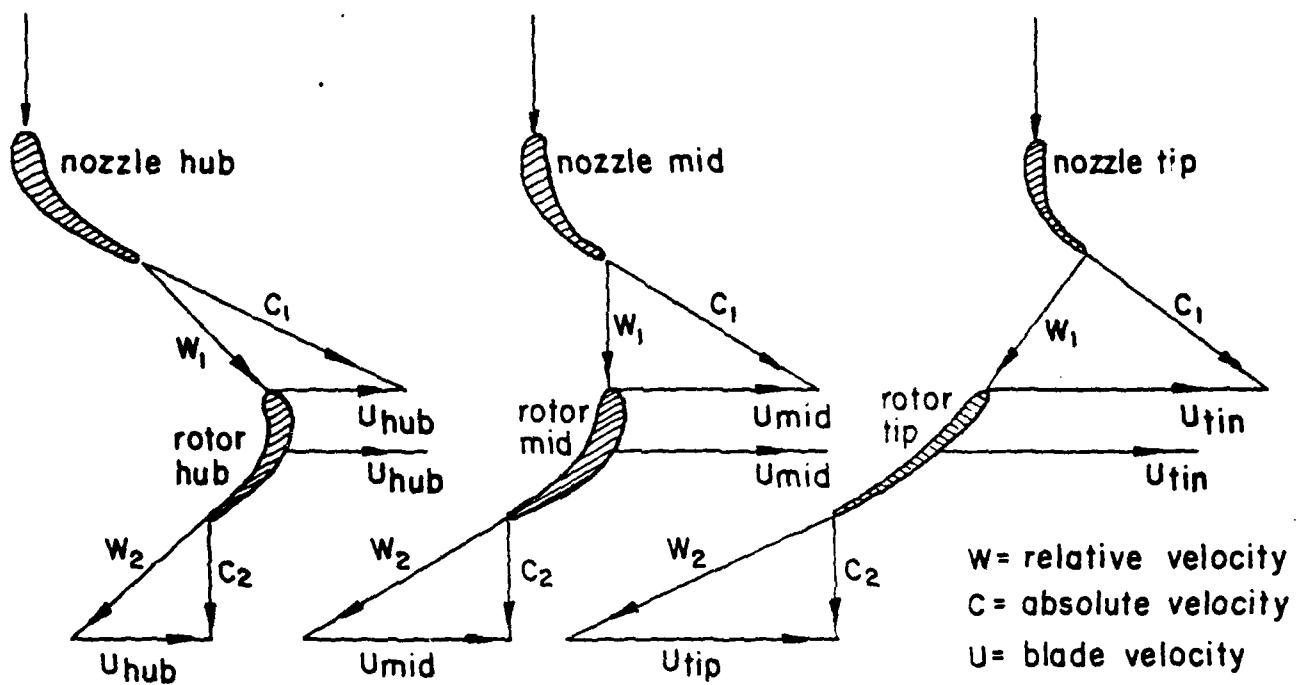


Fig. 4 Correct velocity triangles for reaction turbine stage with low hub tip ratio.

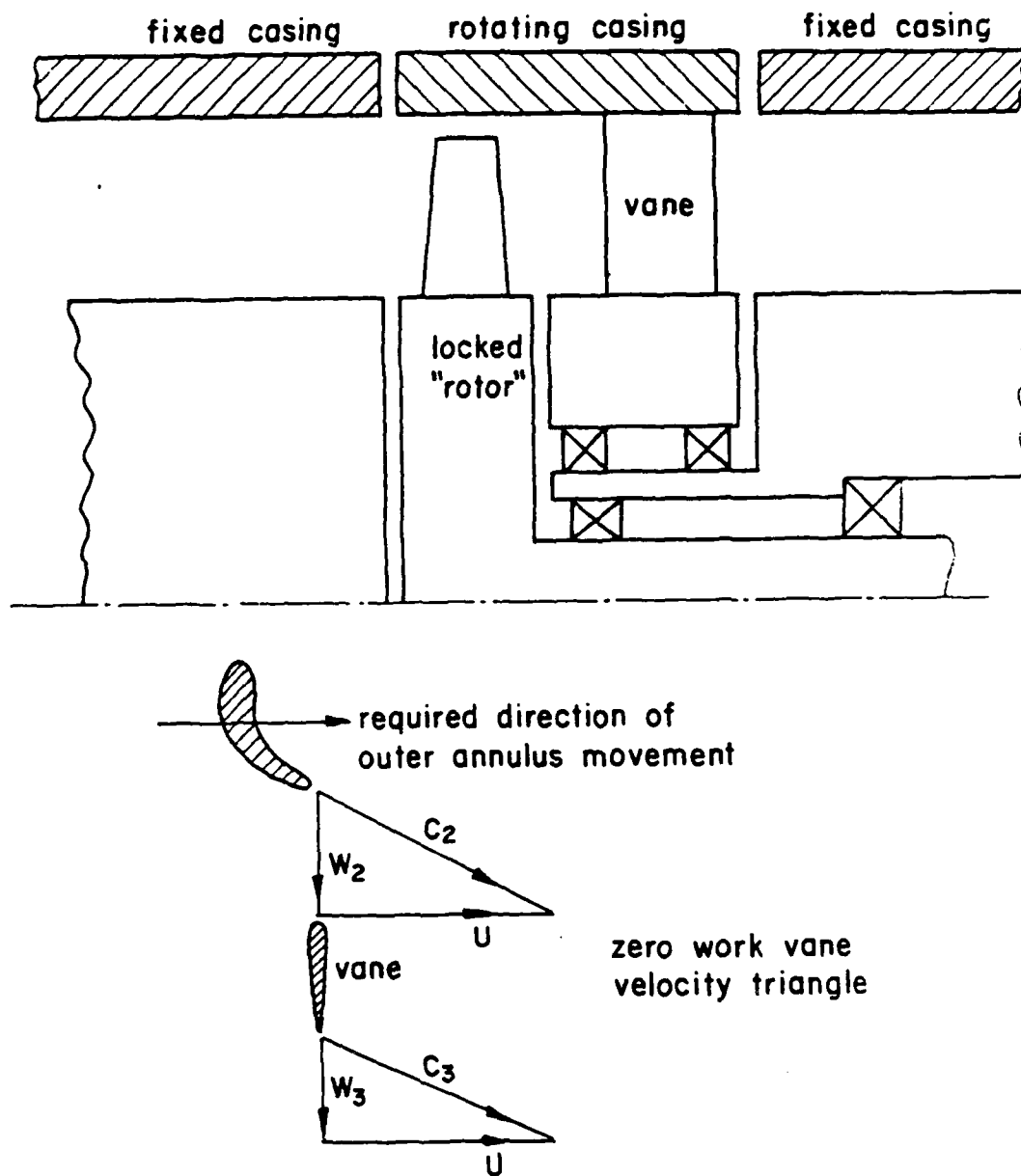


Fig. 5 Velocity triangles and mechanical schematic for rotating casing vane driven experimental rig to simulate relative motion in the tip cavity on a "stationary" rotor model with no periodic nozzle effects.

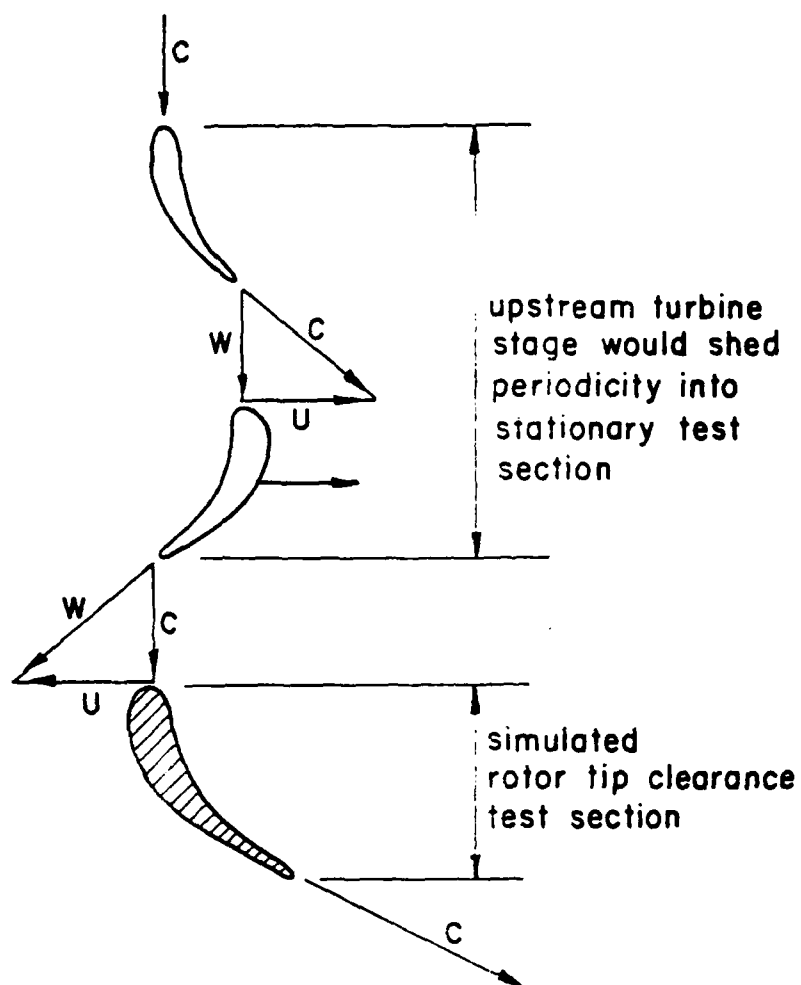


Fig. 6 Upstream turbine stage to simulate periodicity in the stationary rotor tip clearance test section.

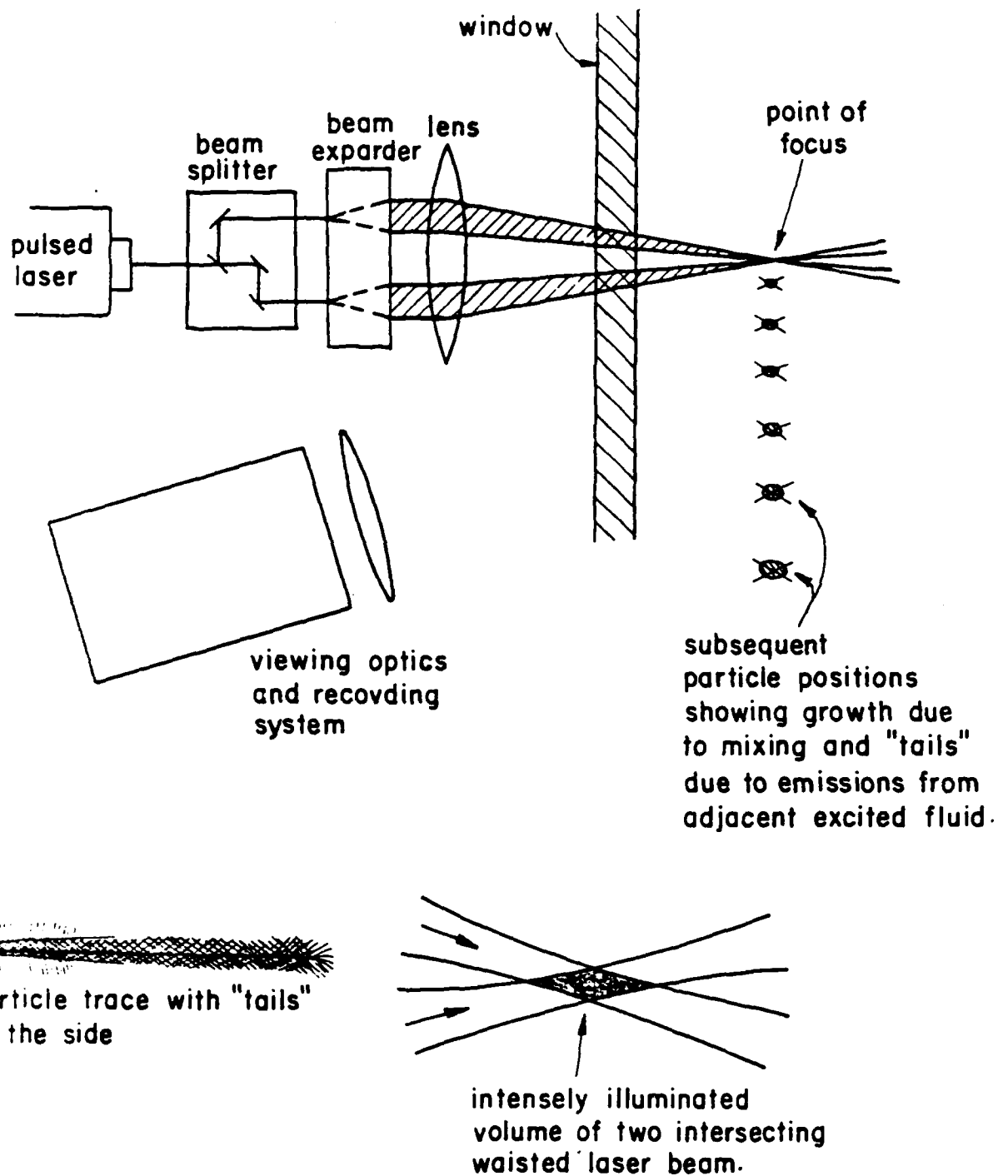


Fig. 7 Multibeam focused spot pulsed laser phosphorescent flow visualisation system.

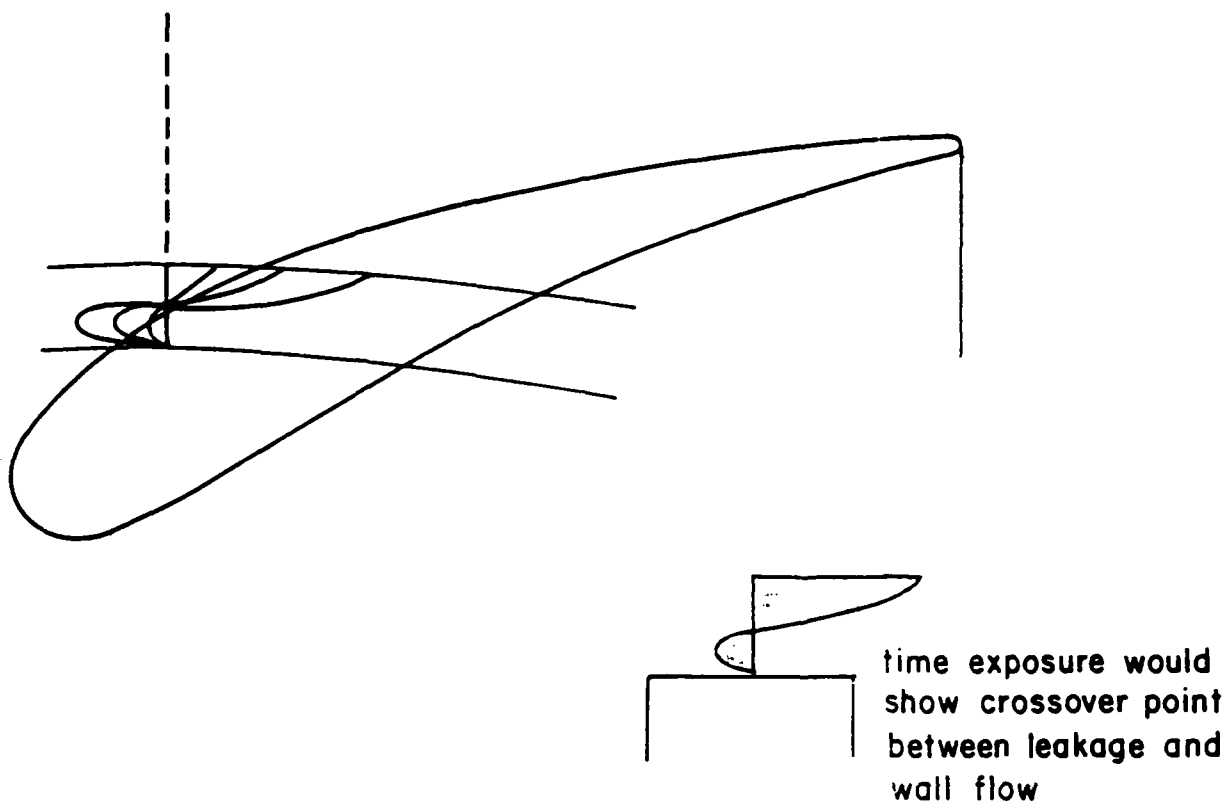


Fig. 8 Pulsed laser pencil beam showing leakage flow profile in clearance gap.

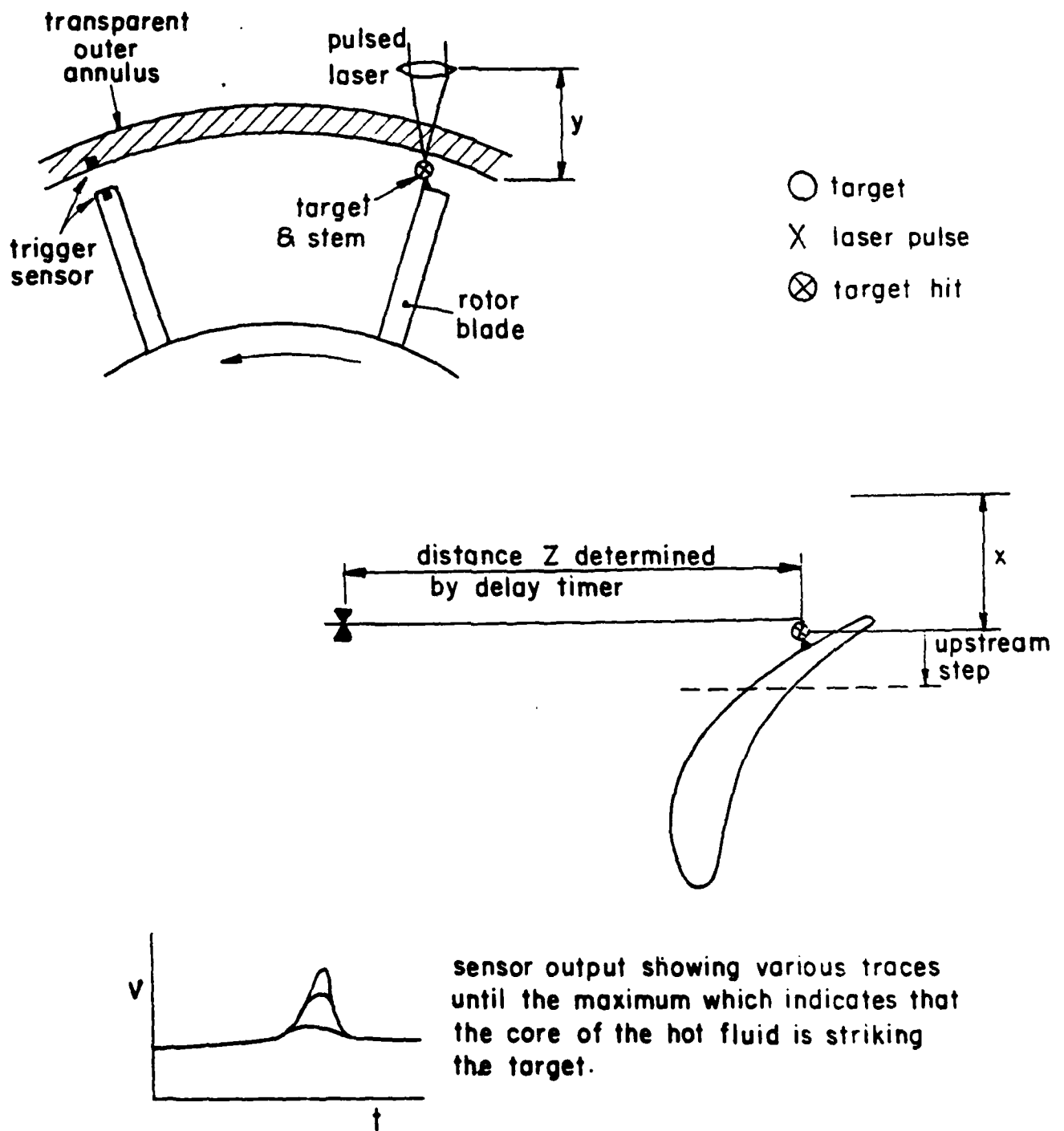
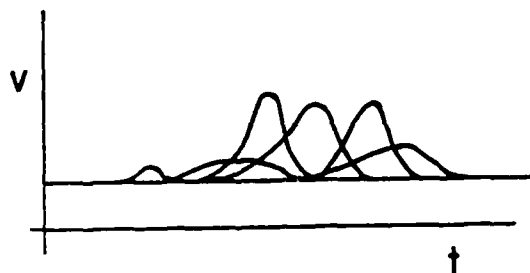
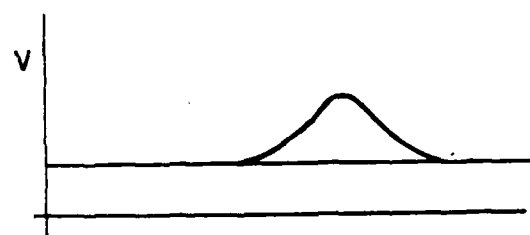


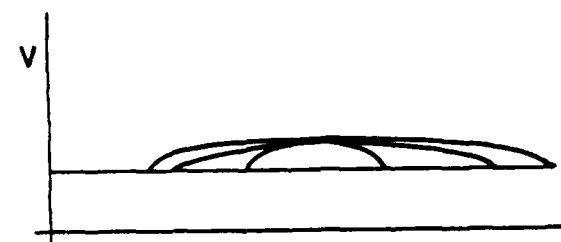
Fig. 9 Pulsed laser phase locked rotor flow visualisation use of rotating sensor and a "fire & search" procedure upstream to map pulse trace.



expected target output due to
turbulent motion moving the
pulse core randomly



Averaging algorithm provides
a single signal



Envelope of averaged signals
when either y or z is varied.
second algorithm provides
optimum y or z values

Fig. 10 Degradation of target sensor output due to mixing and turbulence and extension of technique via statistical treatment of a group of output signals.

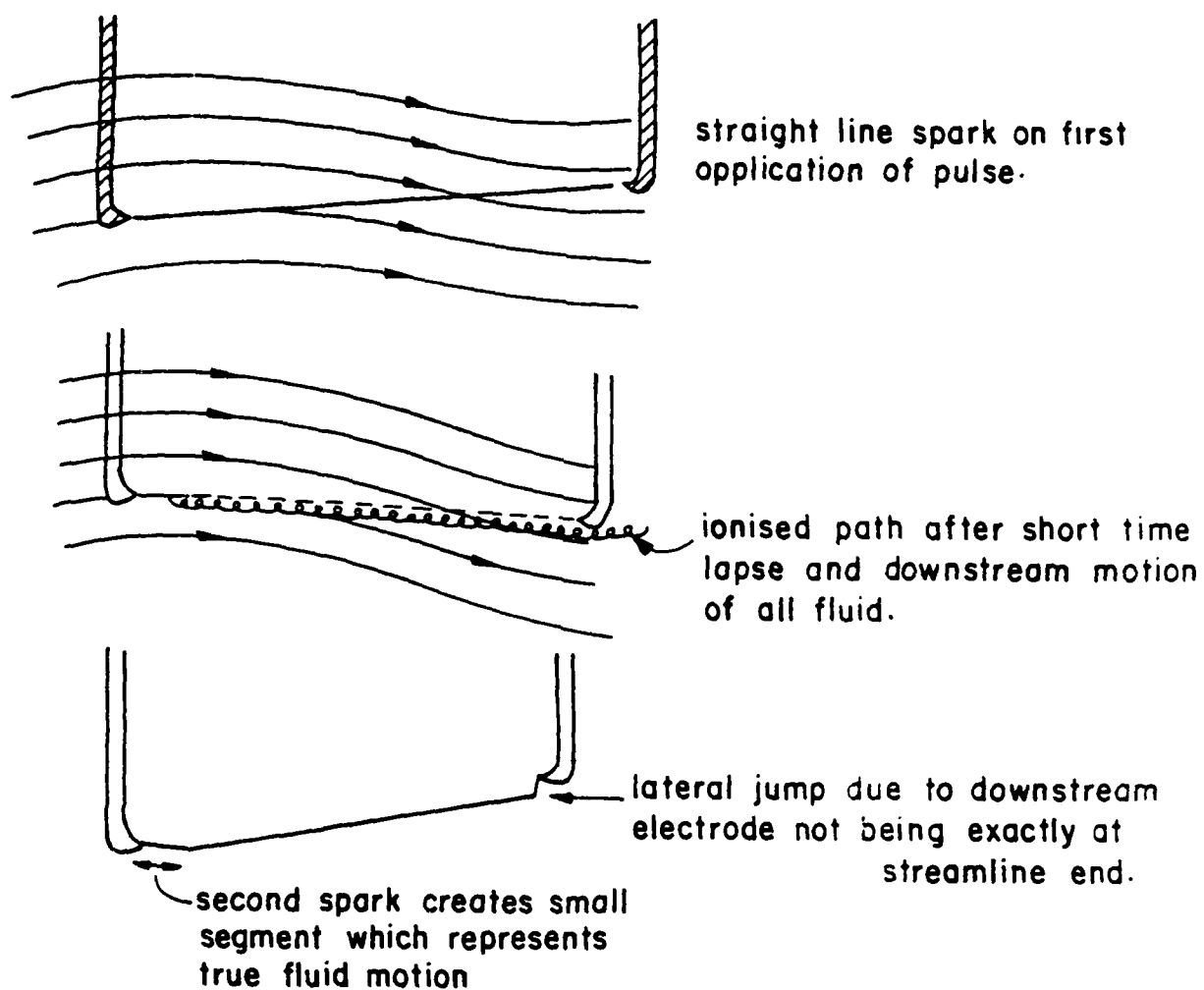


Fig. 11 Principle of creating streamwise sparks which follow fluid motion.

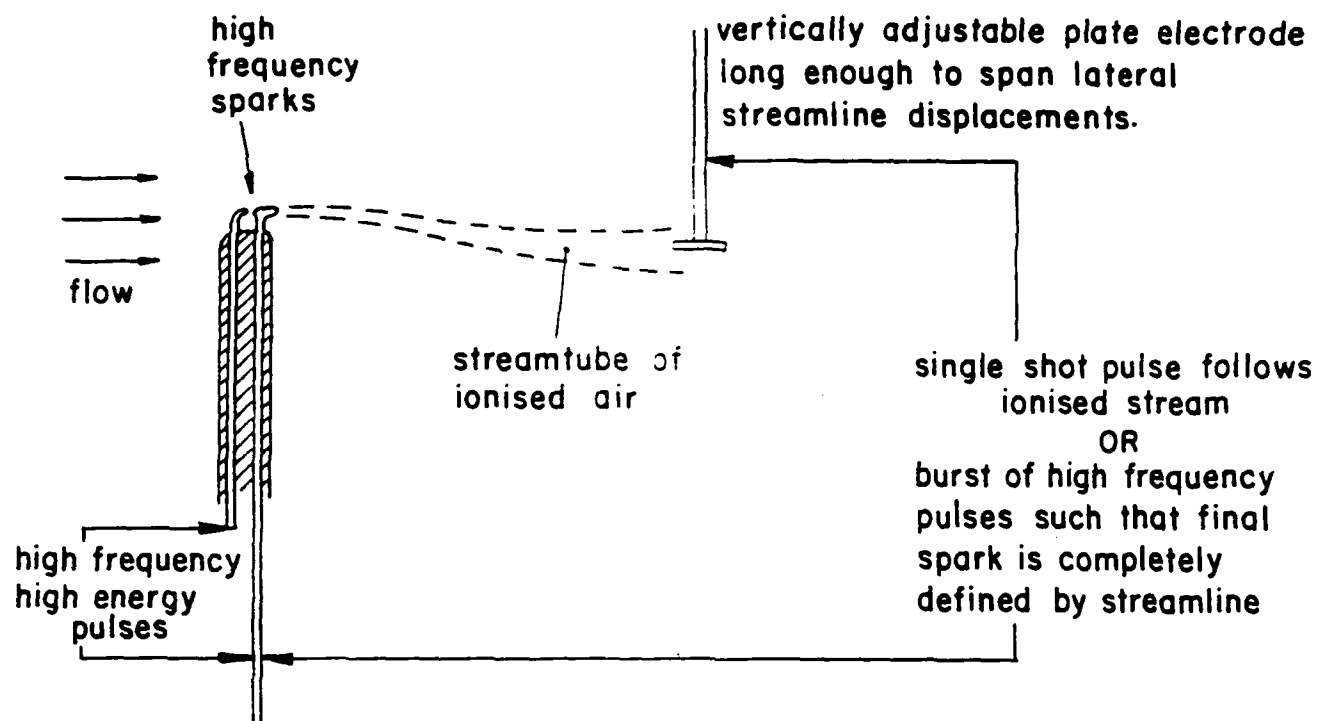


Fig. 12 streamwise spark initiated by the continuous generation of an ionised air streamtube between the two electrodes.

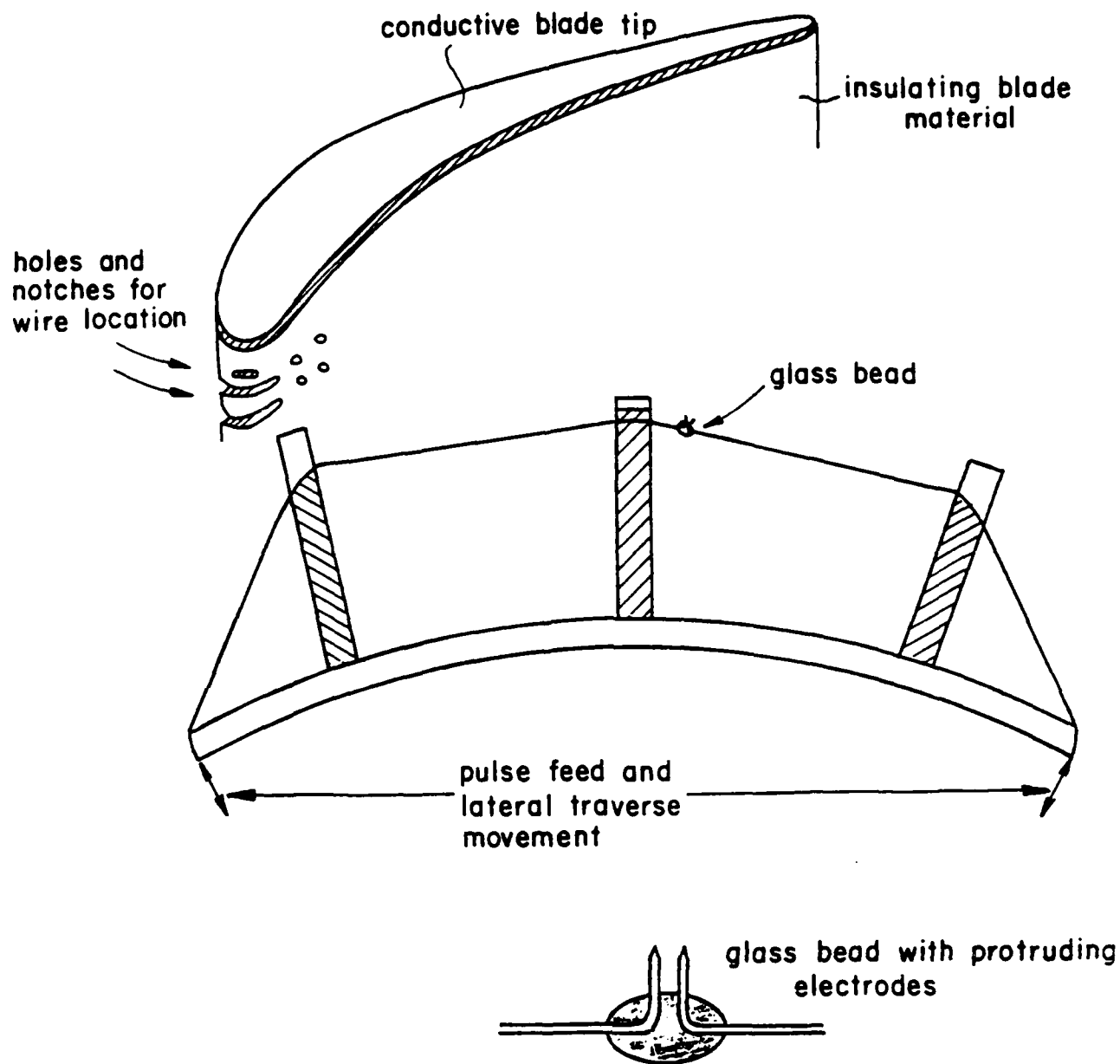


Fig. 13 Spark tracer electrodes created by taut wire technique and blade tip.

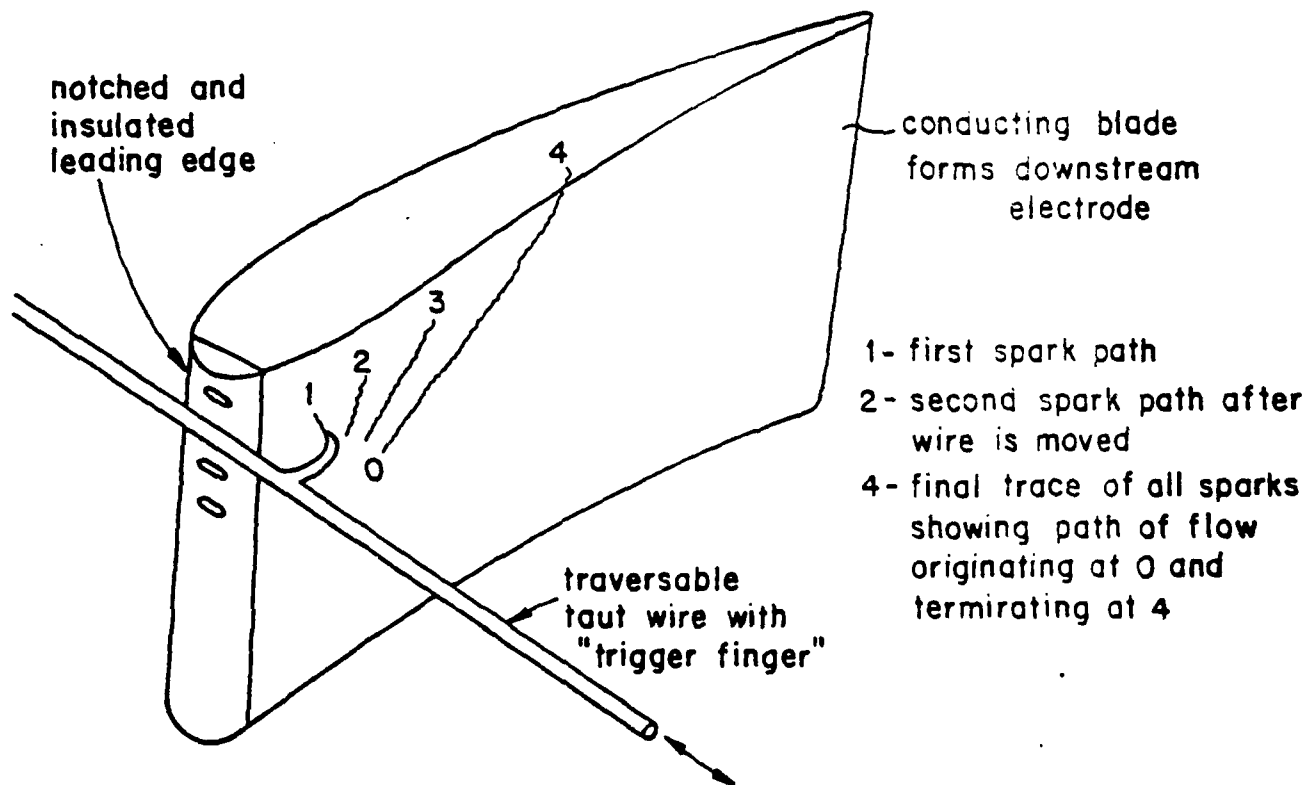
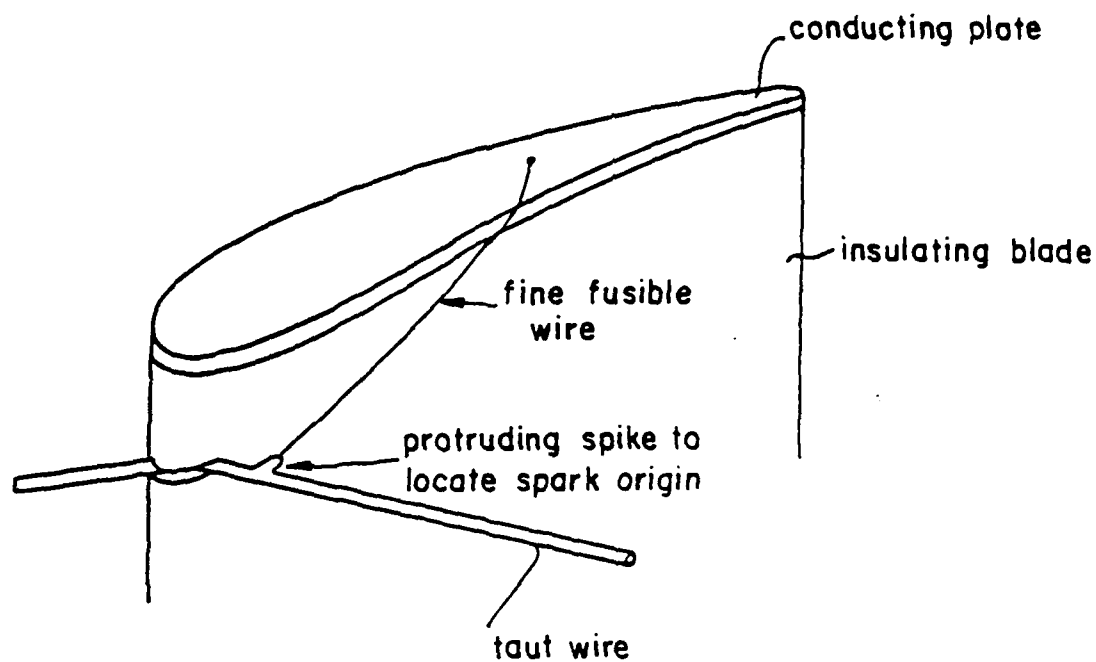


Fig. 14 Alternative methods of triggering the streamline spark.

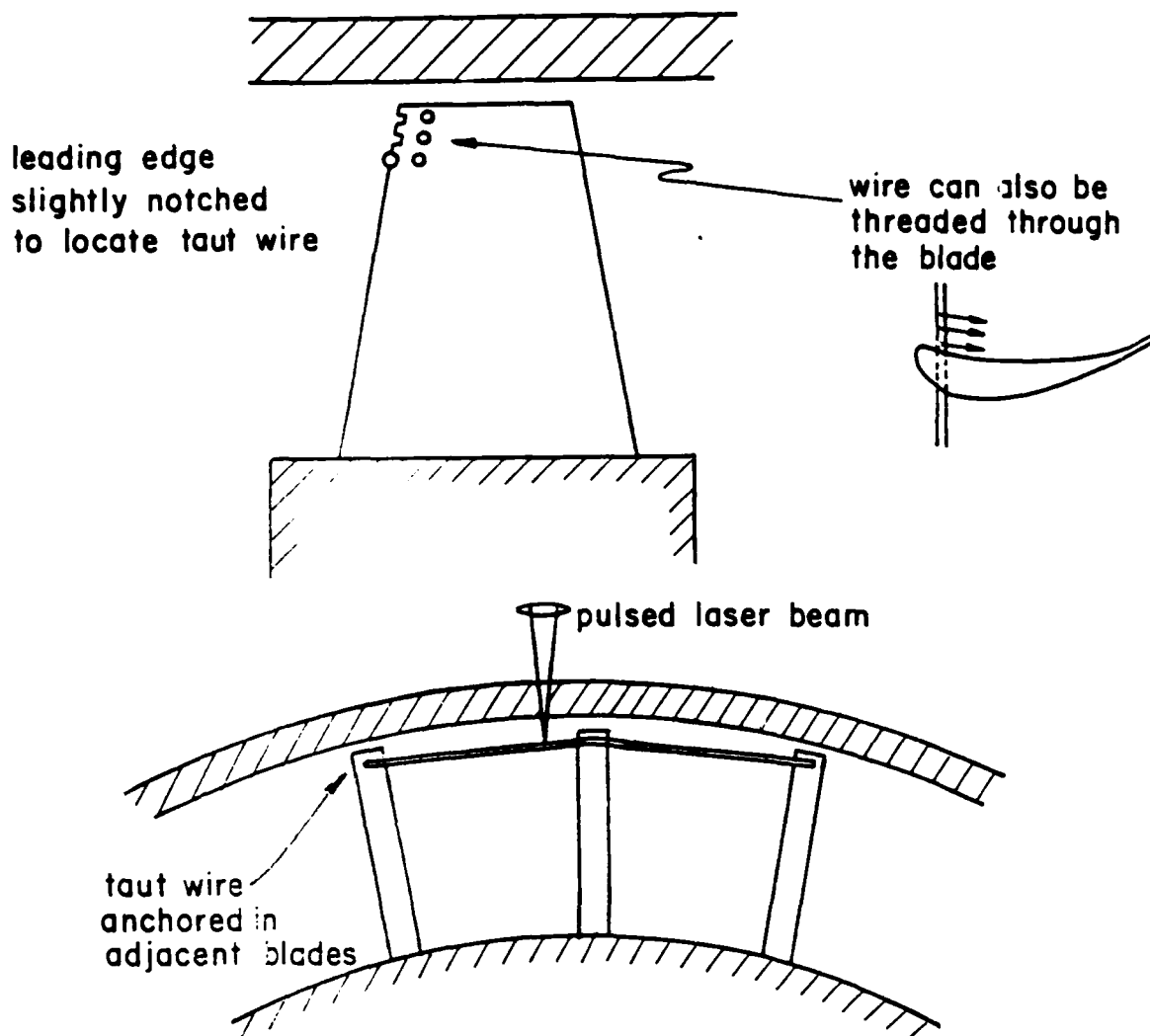


Fig. 15 Localised smoke trace generator using a coated wire located at the correct position and evaporated using a pulsed laser timed for the correct

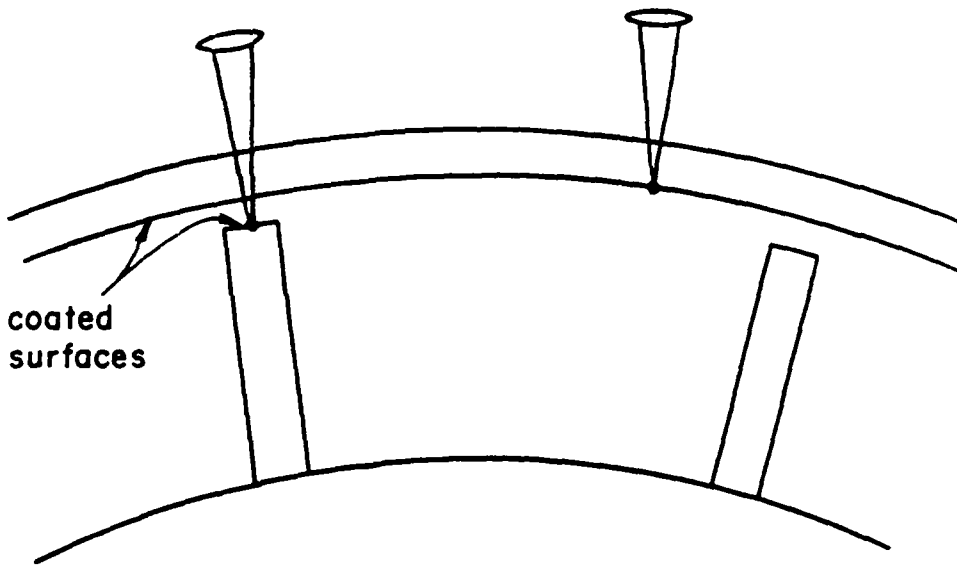


Fig. 16 Laser pulse smoke generation from blade tip clearance and surface and from outer endwall surface.

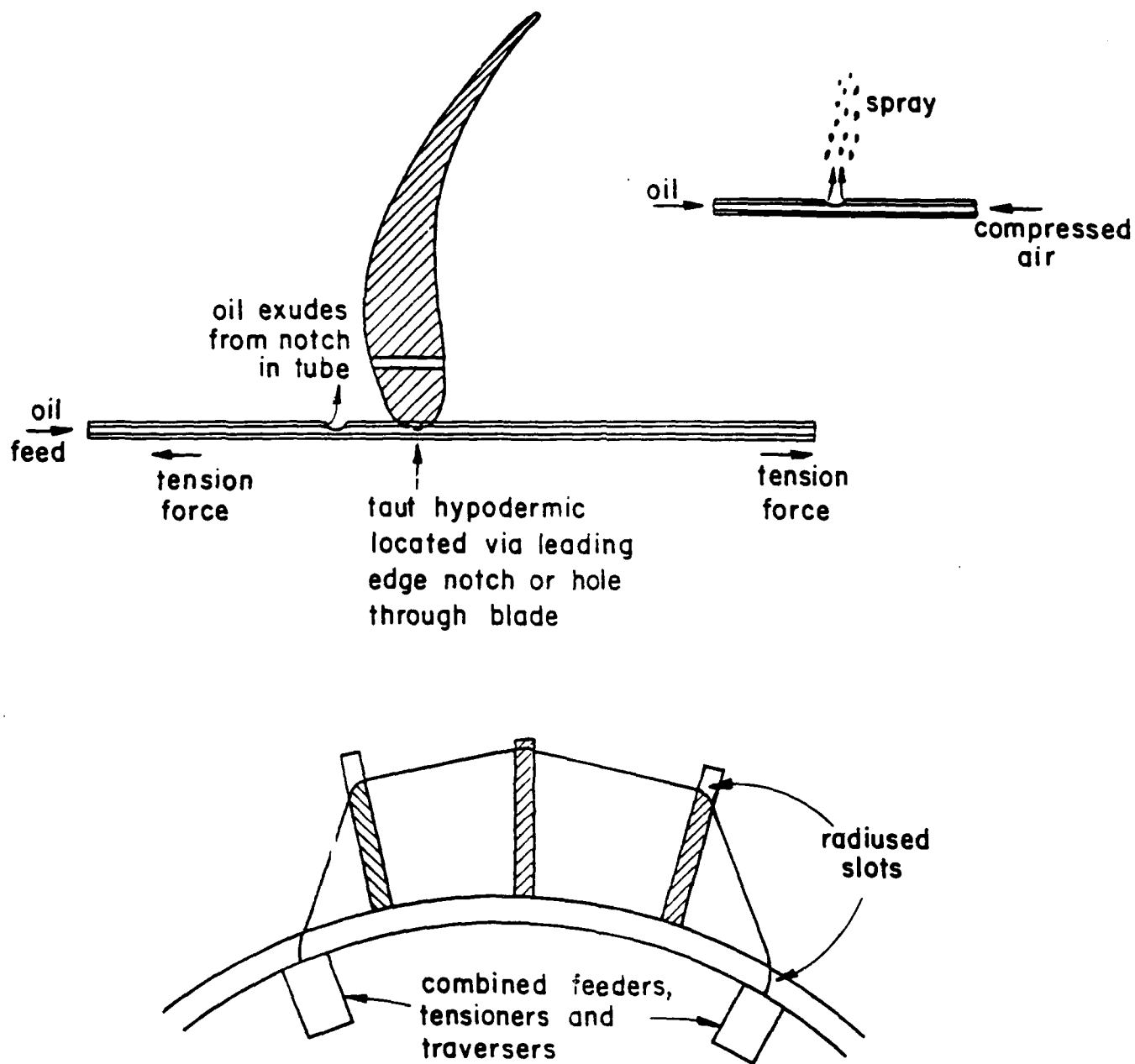


Fig. 17 Laser evaporation of continuously exuded oil or laser pulse smoke generation from oil spray injection.

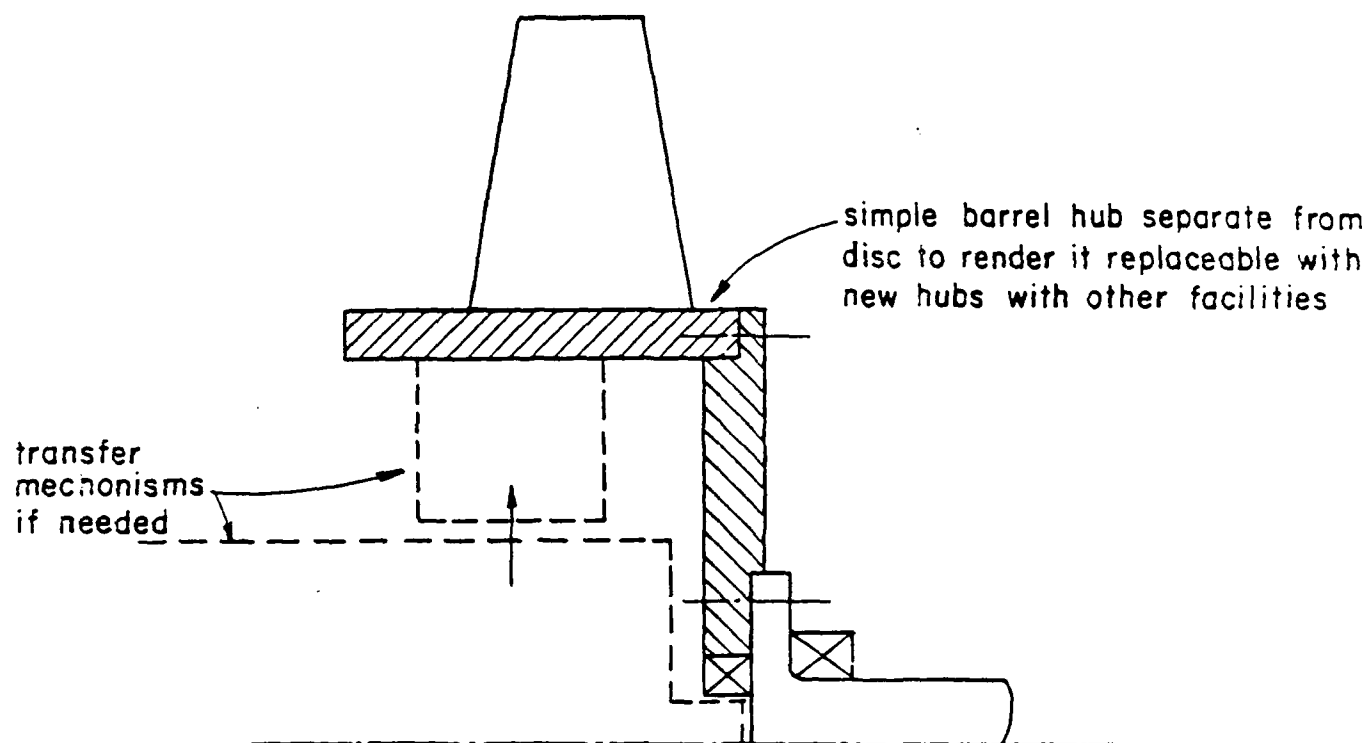


Fig. 18 Suggested rotor hub layout.

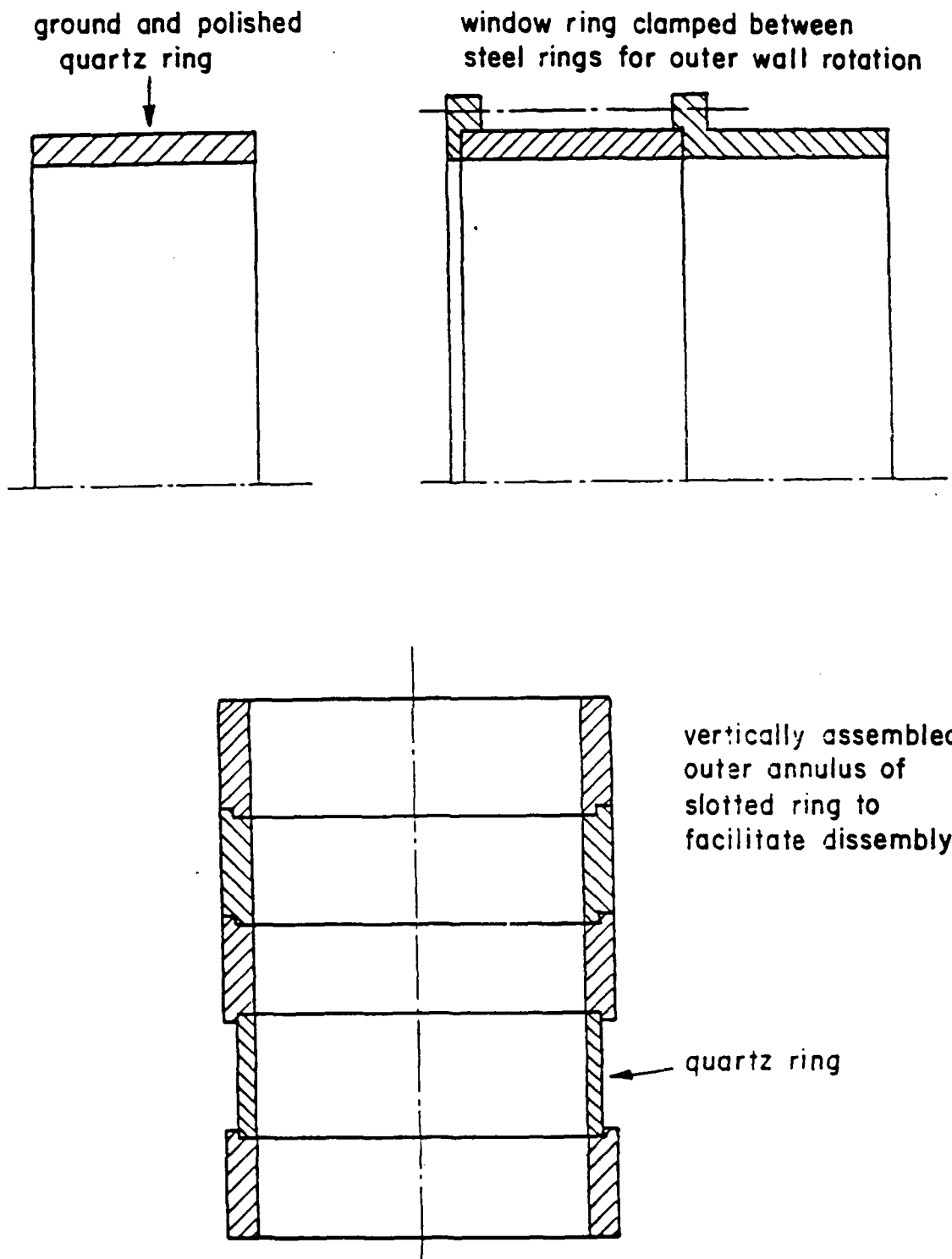


Fig. 19 Suggested outer annulus layout consisting of ground and polished annular quartz window segment and a vertical shaft layout for ease of disassembly.

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